

A CALCULATION MODEL OF FIXED
BED WHEAT AERATION

By

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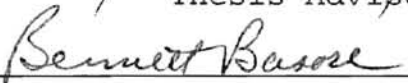
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LIST OF SYMBOLS

A	Constant in Equilibrium Relative Humidity equation
C	Constant in Equilibrium Relative Humidity equation
m	Rate of mass transfer
Ψ	Rate of energy transfer
h	Coefficient of convective heat transfer, $W/(m^2 K)$
k	Thermal conductivity, $W/(m K)$
E	Specific internal energy, kJ/kg
e	Base energy of internal energy
T	Air temperature, $^{\circ}C$
θ	Grain temperature, $^{\circ}C$
H	Specific humidity of dry air, kg/kg
M	Moisture content of product, %db
v_a	Velocity of air, m/s
v_p	Velocity of grain, m/s
ρ_a	Density of air, kg/m^3
ρ_p	Density of grain, kg/m^3
ϵ	Void ratio
c	Specific heat, $kJ/(kg K)$
w	Water content in grain, kg/kg
wb	Wet basis
db	Dry basis

as subscript:

a	Dry air
v	Water vapor
p	Product or grain
w	Water in grain

CHAPTER I

INTRODUCTION

Upon harvesting, wheat moisture content should be reduced by drying to preserve grain quality and to extend the storage time. In addition, decreasing the moisture content controls fungi and insect growth. Grain aeration is also performed to decrease grain temperature and moisture content for proper storing. The main purposes of aeration are to prevent moisture migration and to cool the grain. This process also reduces mold growth, insect activity, and undesirable odors.

Information in Figures 1 through 5 (McLean, 1989) shows the general effects of grain moisture and temperature on grain storage life with regard to grain heating, insects, germination, baking quality, and mites. Information given in each figure shows that the grain storage regions are affected by environment. For instance, Figure 1 shows the effect of temperature and moisture content on grain heating. Figure 2 and Figure 4 show the effect of temperature and moisture content on insects and mites.

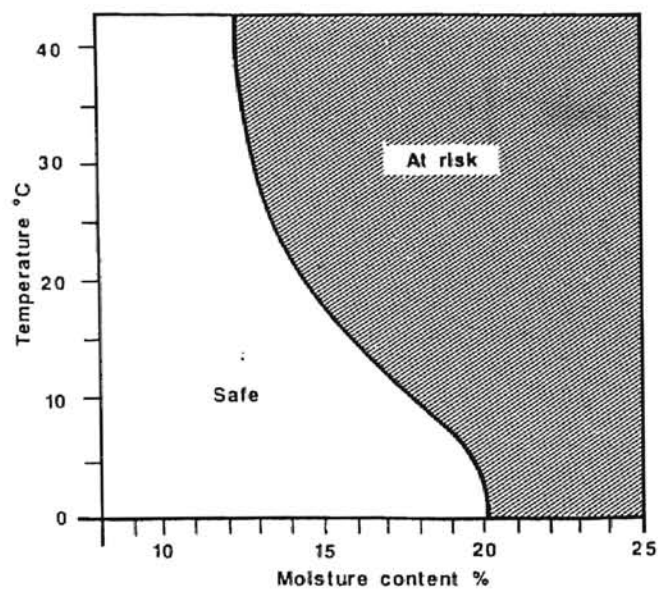


Figure 1. Damaged by grain heating

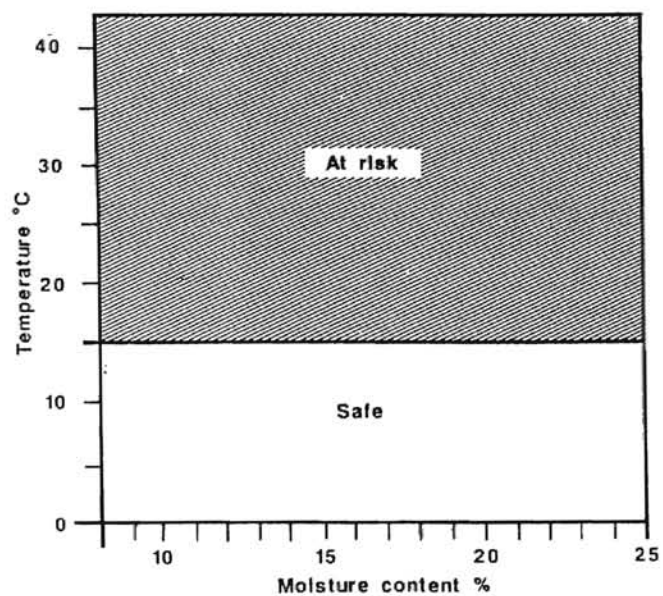


Figure 2. Damaged by insects

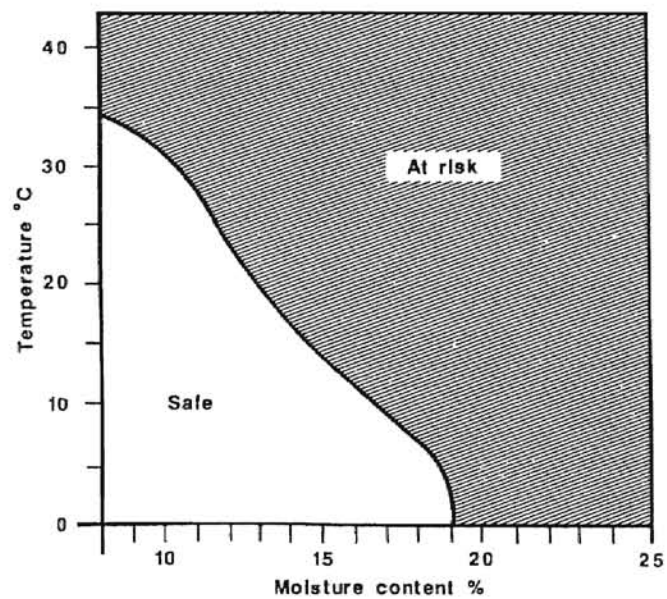


Figure 3. Loss of germination and baking quality

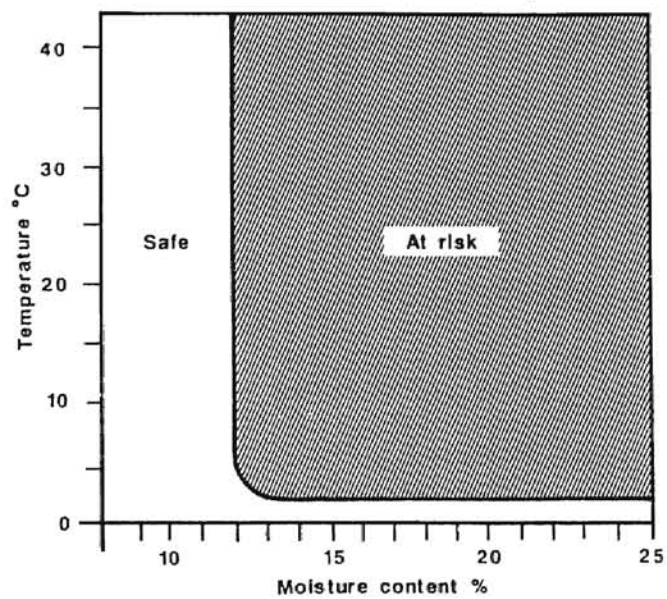


Figure 4. Damaged by mites

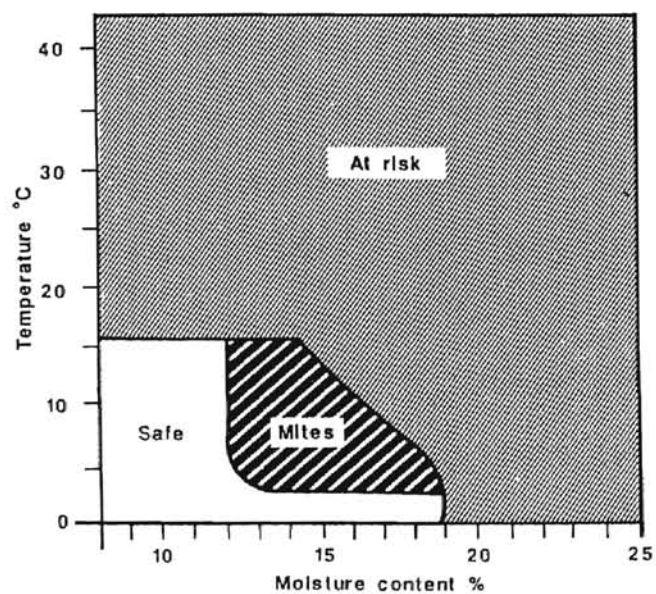


Figure 5. Safe Storage Conditions

Note: Figures 1 through 5 adapted from Mclean (1989)

Information in Figures 1 through 4 is combined in Figure 5 and shows the moisture content and temperature conditions under which wheat can be safely stored. The safe temperature range is between 0°C and 16°C, and the safe moisture content range is between 8 percent and 12 percent wet basis.

Oklahoma has periodic cold fronts in October and November, with ambient temperatures below 10°C. This weather can be utilized to increase the performance of wheat aeration systems in this region.

Although the aeration process can extend the storage time and preserve wheat quality, the factors involved such as air flow rate, temperature, and moisture content must be identified and defined. To find an optimum aeration time, experimental testing must be conducted which will require a lot of effort, time, and cost.

The concept of mass and heat transfer simulation, however, can be used to help reduce the time of actual experimental testing of wheat aeration systems. In addition, it is difficult to conduct experiments in the field or laboratory due to weather conditions and/or size of storage, so computer simulation is needed.

By developing a computer model of mass and heat transfer, where temperatures and humidity can be easily

changed, length of aeration time can be obtained without actual experimental testings.

Purpose of The Study

The purpose of the study was to develop a personal computer calculation model which simulates wheat aeration of a fixed bed bin. A personal computer simulation program will allow farmers and others to easily determine the appropriate air flow rate for their fixed bed aeration, which will results in high quality grain and optimum storage life.

Objectives of the Study

To meet the purpose of the study, the follow objectives were set forth:

1. To develop a calculation model for cooling wheat in a standard fixed bed bin, in order to predict the effects of airflow rate, air temperature, and air humidity on cooling time. The partial differential equation model will be solved by the implicit finite-difference method.
2. To develop a simulation procedure by utilizing a structured programming language.

3. To evaluate simulation performance of the aeration system in a fixed bed wheat storage bin with varying inlet air conditions.

CHAPTER II

LITERATURE REVIEW

Effects of Aeration

Brooker et al.(1974) stated that despite the time that high grain quality can be preserved, which is most important for farmers and others who store grain, the quality of grain will decrease due to the growth of fungi and insects. To prevent the development of insects and fungi, grain temperature and moisture content can be controlled by using aeration.

Aeration (as shown in Figure 6) is usually accomplished by ventilating stored grain with a low air flow rate. The process accomplishes the following:

- Prevents moisture migration by maintaining a uniform temperature through the grain.
- Cools the grain to reduce mold growth and insect activity.
- Helps to eliminate grain odors.

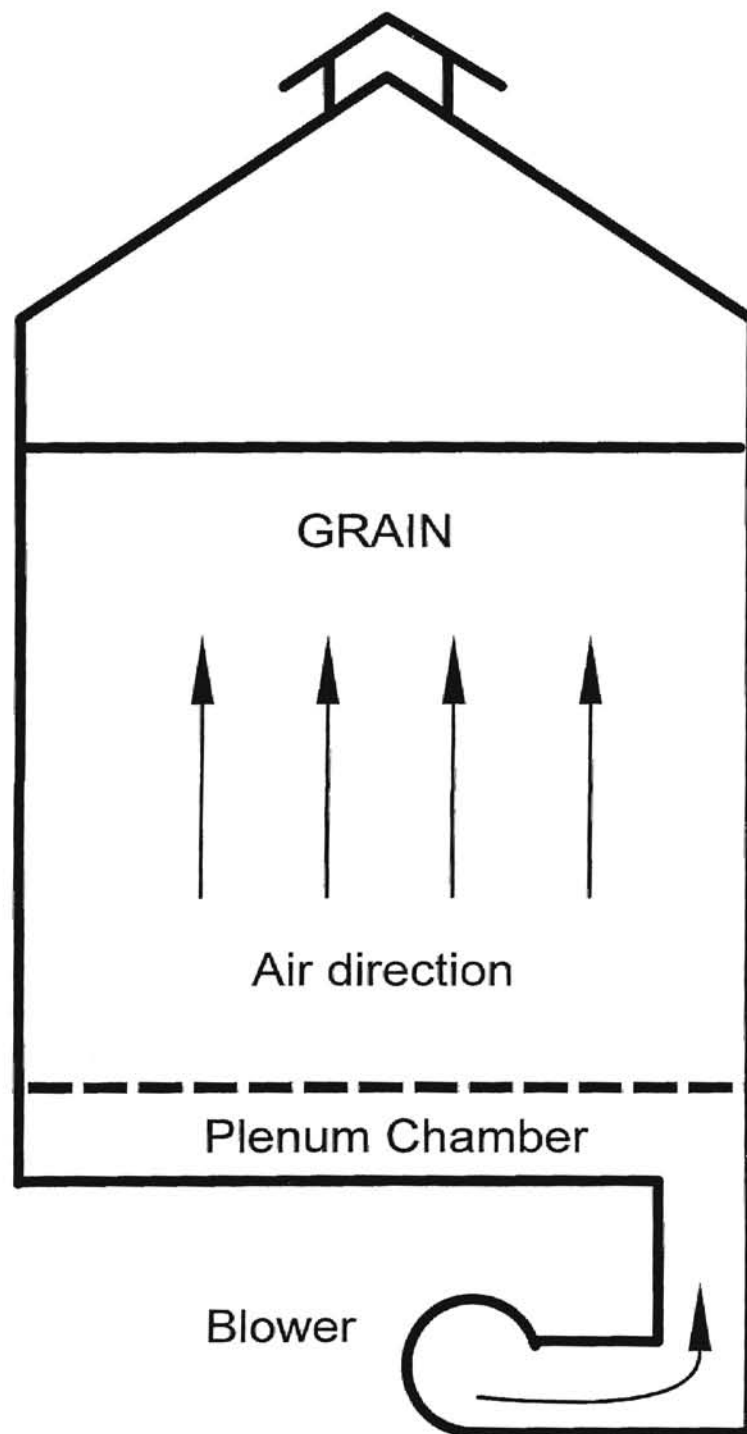


Figure 6. A Typical Grain Aeration

Many experiments on aeration have been conducted to study the preserving of grain. Epperly et al. (1987) conducted an aeration experiment in Oklahoma. They investigated the insect growth rate in two grain bins. Both bins were of the same size and condition, except the first bin used conventional aeration while the second bin used specific (forced) air flow rate aeration. The results showed insect infestation of the second bin to be significantly less than that of the first one (Figs. 7 and 8). It was found that grain temperature had to be kept at about 10°C to 13°C to maintain the ideal range of temperature.

Deep Bed Simulation Model

Several investigations of deep bed calculation models have been conducted to determine suitable models for each particular case such as cooling, heating, and drying. Schuman (1929) may have been the earliest to develop a mathematical model that predicted heating or cooling with a mass of crushed material with fluid flow. His model had many simplifying assumptions such as constant air temperature and air velocity in order to fit the Bessel function form. A reason was that at that time (1929), the modern digital computing machine had not been developed, and

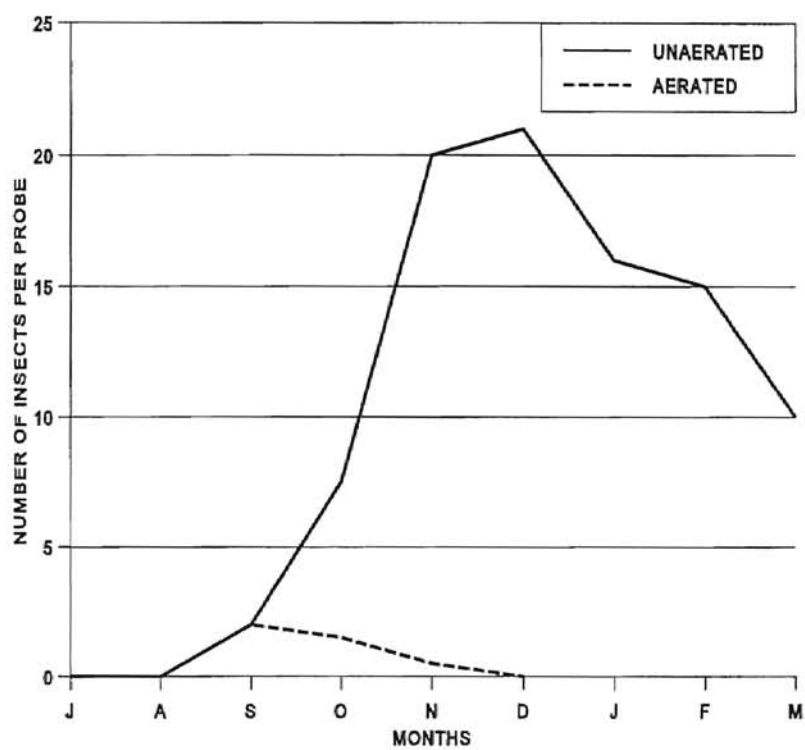


Figure 7. Effect of Aeration on Insect Population in Oklahoma Wheat Storage with Application of Malathion at Binning
(adapted from Epperly et al., 1987)

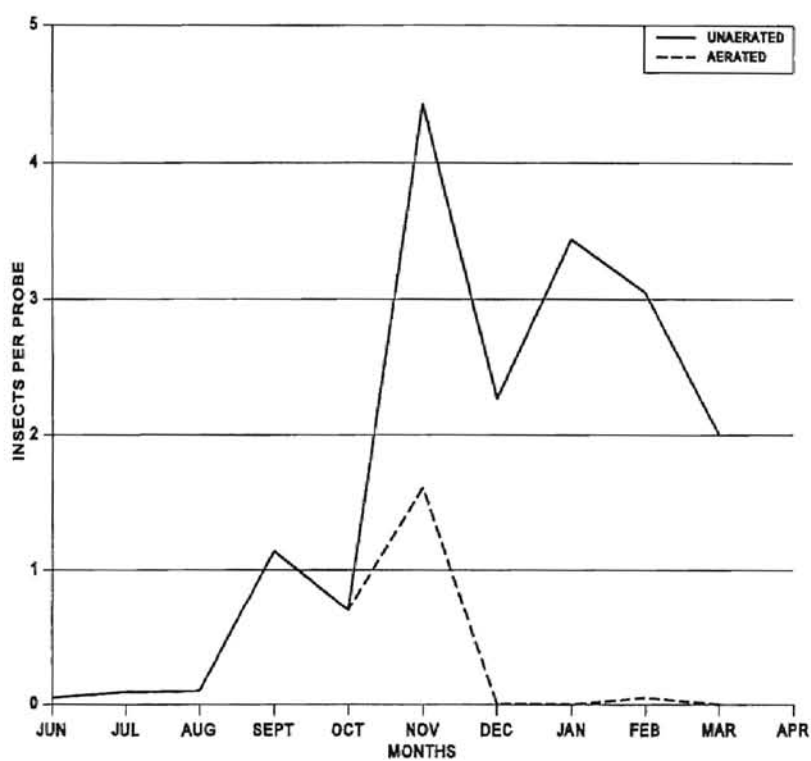


Figure 8. Effect of Aeration on Red Flour Beetles in Oklahoma Wheat Storage.
(adapted from Epperly et al., 1987)

it was not possible to easily find the solution of a mathematical model. Regarding the Bessel function, for which we already know the solution, Schuman's model is in analytical form rather than in numerical form. There is no validation of Schuman's model. However, his work encouraged further investigation of a drying calculation model.

After Schuman's presentation, the methods used to develop mathematical models of deep bed simulation can be classified in three different models. They are:

1. Graphical or logarithmic model
2. Heat and mass balance model
3. Partial differential equation model

Logarithmic Model

Hukill (1954) developed a mathematical model of deep bed grain drying. He used a fully exposed equation of grain drying (eq. 1) and a diffusion differential equation which assumed the rate of moisture lost at some given depth x , after time t , and is proportional to the rate of decrease in air temperature at (x,t) (eq. 2).

$$M - M_e = (M_o - M_e)e^{-kt} \quad (1)$$

$$\frac{dMR}{dt} = C \frac{dT}{dx} \quad (2)$$

By using the similitude technique with boundary and initial condition of deep bed storage, a series of

dimensionless curves was obtained from his equation (Hukill, 1954).

$$MR = \frac{M - Me}{Mo - Me} = \frac{2^x}{2^x + 2^t - 1} \quad (3)$$

where MR = rate of moisture lost

M = grain moisture content

Mo (initial) , Me (equilibrium)

X = dimensionless depth units

t = dimensionless time units

C, k = constant values

This equation provided a simple method for predicting the moisture distribution in a grain drying bin. However, his model under-estimated the time required to dry grain to specific moisture contents.

Because of the model's simplicity and computational economy, some investigators were interested in modifying the logarithmic models to fit their experiments. However, the accuracy was acceptable only at low temperatures and low air flow rates.

Heat and Mass Balance Model

The availability and speed of present day digital computing machines can reduce time and effort in performing more complex calculations. Several investigators, therefore, have developed and presented the deep bed

calculation model utilizing heat and mass balance equations rather than the logarithmic method. Some of the investigations were as follows:

Boyce (1965) conducted barley drying in a 12-inch deep bed. He developed a layer-by-layer technique which was based on thin layer theory to calculate the temperature and moisture content of air and grain. The results showed that the drying times by his calculation were too long. He recommended that more experiments be conducted to determine a better procedure.

Bakker-Arkema et al. (1967) conducted an experiment to cool high moisture content cherry pits in a deep bed. His numerical model, which was based on heat and mass balance conditions, showed good agreement with the experimental results. However, his model was limited to the cherry pit products.

Thompson et al. (1968) conducted corn drying in a deep bed and reported his process as a series of thin layers in which heat and mass balance models were applied (similar to Boyce's model). The results showed an effective model, but limited to certain inlet air conditions.

Henderson and Henderson (1968) used a thin layer calculation model in their experiment on deep bed grain drying. Their numerical results showed that the calculation

time for drying was too long when compared with the actual results.

The calculation models of Bloome (1972), Sutherland et al. (1971), and Ingram (1979) are based on heat and mass balance equations. Consequently, the limitations of these models are their accuracy and range of applicability. In each case, they present some modification to improve the models for their particular conditions. However, all of their suggestions demonstrate the need for further investigation of drying simulation models.

One of the disadvantages of heat and mass balance models is accuracy. This is because the models use the assumption of equilibrium moisture content conditions.

$$M(x,t) = M_e(x,t) \quad (4)$$

$$T(x,t) = \theta(x,t) \quad (5)$$

M = grain moisture content (dry basis)

M_e = grain moisture content at equilibrium

T = air temperature, °C

θ = grain temperature, °C

In a practical situation, equilibrium conditions of grain drying or cooling are not likely to occur, unless the temperature and moisture differences are very low. Therefore, the outcomes of some investigations show predicted time to be longer than actual time. However, the

advantage of simplified equations is that they make the model easy to compute and take less time than the partial differential equation model. The partial differential equation models are more complex and requires a lot of computation time.

In the last decade, the development of digital computing machines has made it easier to handle some partial differential equation models. Investigators continue to develop suitable partial differential equation models utilizing the much faster and more accurate digital computing machines.

Partial Differential Equation Model

During the years from 1960 to 1980, only a few investigators used partial differential equation models in drying simulation, because so much computing time was required and only a few computers were available. However, the partial differential equation models showed a tendency to be more accurate and have a wider range of inlet air conditions.

Morey et al. (1978) stated that beginning in 1966, Michigan State University conducted a series of theoretical analyses to develop a full model of heat and mass transfer simulation. In 1974, Brooker et al. presented drying models

that included physical characteristics such as convective heat and mass transfer coefficients, and air and grain densities, for single kernel drying.

These models used four partial differential equations to predict air temperature, air humidity, grain temperature, and moisture. The finite difference method (F.D.M.) with a time-step calculation was used in the program. However, the performance and accuracy was not high, because an explicit finite difference method was used which did not include an error control technique.

State of The Art

The calculating power of digital computers since 1980 has grown at an exponential rate. These advanced machines have been utilized by researchers in fix bed aeration models. Investigations conducted by Parry (1985) and Costa and Figueiredo (1993) are among the latest.

Parry (1985) presented a mathematical model and described the model as a general mathematical framework of heat and mass transfer in drying particular solids. The assumptions in the model are one-dimensional (1-D) mass flow rates and constant densities for both air and grain, together with neglect of conductive and radiative heating effects, so that convective grain drying can be represented

by a general system of partial differential equations of the form

$$\frac{\partial \bar{U}}{\partial t} + A \frac{\partial \bar{U}}{\partial x} + B \frac{\partial \bar{U}}{\partial y} = \bar{b} \quad (6)$$

Where U = property matrix vector

A = air velocity matrix vector

B = grain velocity matrix vector

b = energy and mass transfer matrix vector

(Details of the equation are given in Chapter III)

With certain simplifying assumptions, Parry stated that other models appearing in the literature could be considered as particular versions of his general models under further appropriate assumptions. For the fixed-bed condition, the model was less complicated. It is believed that Parry's model is the most complete to date.

Costa and Figueiredo (1993) developed a numerical technique for solving the partial differential equations model for a fix bed dryer based on Parry's general model. They proposed a technique to solve the set of partial differential equations by using the characteristic method or by the more conventional finite-difference discretization method. Numerical results from their proposed model were compared with experimental results of Boyce (1965) and showed good agreement.

Costa and Figueiredo's model is not as accurate as Parry's model, but it has the following characteristics: generality, simplicity, reasonable accounting for the essentials of the involved phenomena, and less computing time and storage. Costa and Figueiredo suggest that their proposed model can be used with the dynamic simulation of a fixed bed dryer or other related processes.

Nevertheless, the above investigations of simulation have not been conducted to work with the aeration process or applied to the now universally used personal computers.

Grain Properties

One of the important parts of computer simulation is the accuracy of grain properties. The major properties are thermal conductivity (k_p), specific heat (C_p), bulk density (ρ_b), particle density (ρ_s), and porosity (P).

Epperly (1989) proposed grain properties, used in his aeration experiment, in the following equations.

Thermal conductivity adapted from Chuma et al. (1981).

$$k_p(\text{W/m K}) = 0.144 + 0.0006 M_w \quad (7)$$

Specific heat adapted from Mohensin (1980).

$$C_p(\text{kJ/kg K}) = 1.258 + 0.01131 M_w \quad (8)$$

M_w = grain moisture content % wb

Bulk density is the weight of a mass of intact individual units of the material packed in a given volume (including pore space) by a specific method. Epperly used 750 kg/m^3 for soft white wheat for moisture content of 0% to 10%. For each 1% increase in moisture content above 10%, the density decreases by 3.7 kg/m^3 .

Porosity (P) can be calculated from bulk density and particle density as:

$$P = 1 - (\rho_b / \rho_s) \quad (9)$$

Where ρ_b = Bulk density

ρ_s = Particle density

CHAPTER III

METHODOLOGY

Models developed by using partial differential equations (P.D.E.) of energy and mass transfer have the advantage of greater accuracy and parametric flexibility. However, it is more complicated and time consuming than the heat and mass balance method.

At the present, due to the high-speed central processing unit (CPU) of digital computing machines, including personal computers, the partial differential equation can be numerically solved with relatively short computation time. The problem encountered in the past, utilizing the partial differential equation models, has been eliminated. In addition, new investigations on parameters, for instance, convective heat transfer coefficient, have been conducted and the conclusions revised so that it can be easily updated in the simulation program.

The simulation model developed by this researcher was based on Parry's (1985) general model (eq. 6). Modifications were made on the assumption that heat and mass

transfer during aeration is slower than that of the drying process. Partial differential equations can be set in vector form and solved by the appropriate methods (Crank-Nicolson or Runge Kutta, Costa and Figueiredo, 1993).

The procedure used for developing the computer simulation program was as follows:

1. Developed a simulation model based on Parry's general models, with the equation modified for fixed bed aeration.

The boundary and initial conditions were:

$$t = 0, \quad T_o = T(x), \quad H_o = M(x)$$

$$t = \infty, \quad T(x) = T_o, \quad M(x) = H_o$$

2. Simplified the model with the assumption proposed by Costa and Figueiredo (1993). In the fixed bed, heat and mass transfer during aeration were likely to be at equilibrium moisture content state. The assumptions were:

- Air flow in one dimension is at a constant velocity;
- Lateral dryer walls are adiabatic and impermeable;
- Conduction of heat and moisture between particles is negligible;
- No shrinkage of bed occurs;
- Total air pressure is constant through the bed;

- Physical properties (density and specific heat) of dry air and solids, liquid water, and water vapor are constants;
- Longitudinal mass and heat dispersion in the air flow are negligible;
- No initial gradient of moisture and temperature exists within the solid particles;
- The mass transfer rate from the solid to the air is described by the drying kinetics equation (or thin layer drying rate equation, $\partial M / \partial t = -k(M - M_e)^n$).

3. Used numerical techniques as in Costa and Figueiredo's proposed model. The numerical solutions were obtained by using semi-implicit finite-difference methods (Crank-Nicolson).

Mathematical Models

The program mathematical model was developed based on Parry's general models (eq. 6).

$$\frac{\partial \bar{U}}{\partial t} + A \frac{\partial \bar{U}}{\partial x} + B \frac{\partial \bar{U}}{\partial y} = \bar{b} \quad (10)$$

Where

$$U = [H, M, T, \theta]^T$$

$$A = \begin{bmatrix} v_a & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & v_a & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & v_p & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & v_p \end{bmatrix}$$

$$b = \begin{bmatrix} b1 \\ b2 \\ b3 \\ b4 \end{bmatrix} = \begin{bmatrix} m/\epsilon\rho_a \\ -m/\epsilon\rho_a \\ \{-\Psi - mE_v(T)\}/\{\epsilon\rho_a(c_a + c_vH)\} \\ \{\Psi + mE_w(\theta)\}/\{\rho_p(c_p + c_vM)\} \end{bmatrix}$$

where: $E_v(T) = e_v + c_vT$

$E_w(\theta) = e_w + c_w\theta$

m = rate of mass transfer, kg/s

Ψ = rate of energy transfer from

$\Psi = h(T - \theta) - mE_v(\theta_v)$, J/s

h = heat transfer coefficient, J/kg °C

E = specific internal energy, J/kg

e = base energy of internal energy, J/kg

T = air temperature, °C

θ = grain temperature, °C

H = specific humidity of dry air, kg/kg

M = moisture content of product, %db

v_a, v_p = velocity of moist air and product, m/s

ρ_a, ρ_p = density of air and product, kg/m³

ϵ = void ratio

c = specific heat, kJ/kg K

w = water in grain, kg/kg

suffix a = dry air, v = water vapor

p = product, w = water in grain

Applied to the fixed bed case, with one dimension and grain velocity = 0, equation (1) reduces to

$$\frac{\partial \bar{U}}{\partial t} + A \frac{\partial \bar{U}}{\partial x} = \bar{b} \quad (11)$$

Because of low temperature differences and airflow rates, near equilibrium conditions were produced between air and grain during aeration. Since the Biot Number (h_l/k) is low and airflow rates are low, grain temperature and air temperature were assumed to be equal at equilibrium moisture content conditions.

$$\text{hence,} \quad M(x, t) = M_e(x, t)$$

$$T(x, t) = \theta(x, t)$$

M_e = grain moisture content at equilibrium

(x, t) = space and time

the final vector matrix will be

$$A \frac{\partial \bar{U}}{\partial t} + B \frac{\partial \bar{U}}{\partial x} = \bar{0} \quad (12)$$

Where

$$U = [H, T]^T$$

$$A = \begin{bmatrix} \epsilon \rho_a + \rho_p \frac{\partial Me}{\partial H} & \rho_p \frac{\partial Me}{\partial T} \\ \rho_p v \frac{\partial Me}{\partial H} & \epsilon \rho_a c1 + \rho_p (c2 + \frac{\partial Me}{\partial T}) \end{bmatrix}$$

$$B = \begin{bmatrix} \epsilon \rho_a v_a & 0 \\ 0 & \epsilon \rho_a v_a c1 \end{bmatrix}$$

where $v = c_w \theta - c_v T - hfg$

$c1 = c_a + c_v H,$

$c2 = c_p + c_w M$

$hfg = \text{latent heat, kJ/kg K}$

The equation can be solved by using the semi-implicit scheme by Crank-Nicolson.

CHAPTER IV

COMPUTER PROGRAM DEVELOPMENT

The computer program was developed as a main program and subroutines. C language, a structured programming language, was used to code the program. Two characteristics of a structured programming language is that; one(1), it runs from top to bottom and, two(2) as a subroutine, it has only one specific output for any given inputs. These characteristics make the program easy to read, correct (debug), and modify.

The over-all program development is discussed under main program and subroutine programs.

Main Program

The purposes of the main program are to control and call the subroutine programs. In addition, the main program will perform the following tasks:

- Initialize parameters, physical constants of grain air and water.
- Get input conditions, such as rate of air flow and temperatures.

- Call a subroutine to calculate next-step conditions.
- Check prediction errors and make calculations (iteration loop).
- Print out results.

Listing of the program is presented in Appendix C.

Figure 9 shows the flow chart of the main program.

Constraint Subroutine Programs

Temperature and Humidity Computer Model

The major part of the computer program is a temperature and humidity prediction subroutine. A computer model was developed from the system of partial differential equation (eq. 12). The Crank Nicolson's method (semi-implicit finite difference) was used to solve the computer model for temperature and humidity prediction. Equation (12) can be expanded as follows;

$$\left(\epsilon \rho_a + \rho_p \frac{\partial Me}{\partial H} \right) \frac{\partial H}{\partial t} + \left(\rho_p \frac{\partial Me}{\partial T} \right) \frac{\partial T}{\partial t} + \epsilon \rho_a v_a \frac{\partial H}{\partial x} = 0 \quad (13)$$

$$\left(\rho_p \gamma \frac{\partial Me}{\partial H} \right) \frac{\partial H}{\partial t} + [\epsilon \rho_a C1 + (C2 + \gamma \frac{\partial Me}{\partial T})] \frac{\partial T}{\partial t} + \epsilon \rho_a v_a C1 \frac{\partial T}{\partial x} = 0 \quad (14)$$

from eq. (13) and (14), rearranging to (15) and (16),

$$\epsilon \rho_a \frac{\partial H}{\partial t} + 2 \rho_p \frac{\partial Me}{\partial t} = -\epsilon \rho_a v_a \frac{\partial H}{\partial x} \quad (15)$$

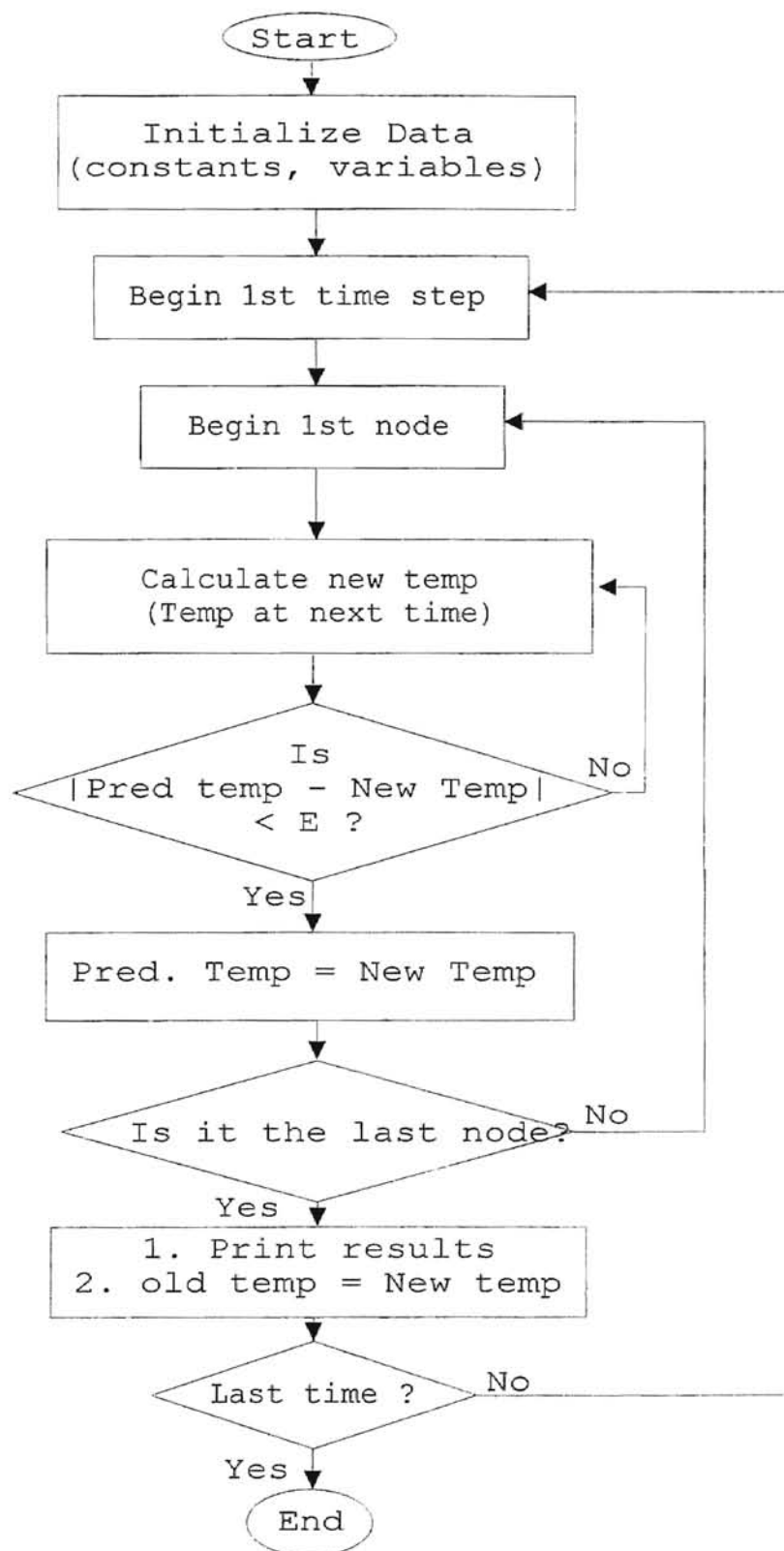


Figure 9. Flow Chart of Main Program

$$(\epsilon \rho_a C1 + \rho_p C2) \frac{\partial T}{\partial t} + 2 \rho_p \gamma \frac{\partial Me}{\partial t} = -\epsilon \rho_a v_a C1 \frac{\partial T}{\partial x} \quad (16)$$

In order to find a numerical solution, the system of partial differential equation (eq. 15 and 16) were transformed to finite difference form by assuming constants as follows;

$$A = \epsilon \rho_a \quad : \quad B = 2 \rho_p \quad : \quad C = -\epsilon \rho_a v_a$$

$$D = (\epsilon \rho_a C1 + \rho_p C2) \quad : \quad E = 2 \rho_p \gamma \quad : \quad F = -\epsilon \rho_a v_a C1$$

Where m is the starting point (known value), n is the time at point m, and the symbol ' is for the next time step.

At point m, time n, the finite difference equation that represents eq.(15) becomes:

$$\frac{A(H_m' - H_m)}{\Delta t} + \frac{B(Me_m' - Me_m)}{\Delta t} = \frac{C(H_m - H_{m-1})}{\Delta x} \quad (17)$$

At point m, time n+1, the finite difference equation that represents eq.(15) becomes:

$$\frac{A(H_m' - H_m)}{\Delta t} + \frac{B(Me_m' - Me_m)}{\Delta t} = \frac{C(H_m' - H_{m-1}')}{\Delta x} \quad (18)$$

Summation of eq.(17) and eq.(18) is the be semi-implicit finite difference form, or Crank-Nicolson form.

$$2A(H_m' - H_m) + 2B(Me_m' - Me_m) = C \frac{\Delta t}{\Delta x} (H_m' - H_{m-1}' + H_m - H_{m-1})$$

let $\Delta t / \Delta x = \beta$,

$$(2A - C\beta)H_m' = C\beta(H_m - H_{m-1} - H_{m-1}') + 2AH_m - 2B(Me_m' - Me_m)$$

To find the absolute humidity of aeration at point m and time $n+1$, the equations were arranged to form the final equation:

$$H_m' = H_m - \left(\frac{\beta}{2A/C - \beta} \right) (H_{m-1} + H_{m-1}') - B(Me_m' - Me_m) \quad (19)$$

For grain temperatures, eq.(16) was used by the same method to develop a finite difference of Crank-Nicolson form.

At point m , time n , the finite difference equation that represents eq.(16) becomes:

$$\frac{D(T_m' - T_m)}{\Delta t} + \frac{E(Me_m' - Me_m)}{\Delta t} = \frac{F(T_m - T_{m-1})}{\Delta x} \quad (20)$$

At point m , time $n+1$, the finite difference equation that represents eq.(16) becomes:

$$\frac{D(T_m' - T_m)}{\Delta t} + \frac{E(Me_m' - Me_m)}{\Delta t} = \frac{F(T_m' - T_{m-1}')}{\Delta x} \quad (21)$$

Summation of eq.(20) and eq.(21) is the semi-implicit finite difference form, or Crank-Nicolson form.

$$2D(T_m' - T_m) + 2E(Me_m' - Me_m) = F \frac{\Delta t}{\Delta x} (T_m' - T_{m-1}' + T_m - T_{m-1})$$

let $\Delta t / \Delta x = \beta$,

$$(2D - C\beta)T_m' = F\beta(T_m - T_{m-1} - T_{m-1}') + 2DT_m - 2E(Me_m' - Me_m)$$

To find the absolute humidity of aeration at point m and time $n+1$, the equation were arranged to form the final

equation:

$$T_m' = T_m - \left(\frac{\beta}{2D/F - \beta} \right) (T_{m-1} + T'_{m-1}) - E(Me_m' - Me_m) \quad (22)$$

Equation (19) and (22) were the simulation models which were computer coded to the subroutine program, 'calc_T_H'.

Figure 10 shows a flow chart of the subroutine program.

Equilibrium moisture content model

Pfost et al. (1976) presented the equilibrium moisture content(emc) equation for wheat as follows.

$$ERH = 1 - \exp(-A(T + C)emc^N)$$

Where T = Temp, °F (dry bulb)

emc = equilibrium moisture content, % dry basis

ERH = equilibrium relative humidity, decimal unit

For hard red winter wheat,

$$A = -0.000023008 \text{ (°F)}^{-1}$$

$$C = 55.815 \text{ °F}$$

$$N = 2.2857$$

so,

$$ERH = 1 - \exp(-0.000023008(T + 55.815)emc^{2.2857}) \quad (23)$$

Hence, emc can be defined as,

$$emc^{(2.2857)} = \frac{\ln(1-ERH)}{-0.000023008(T + 55.815)} \quad (24)$$

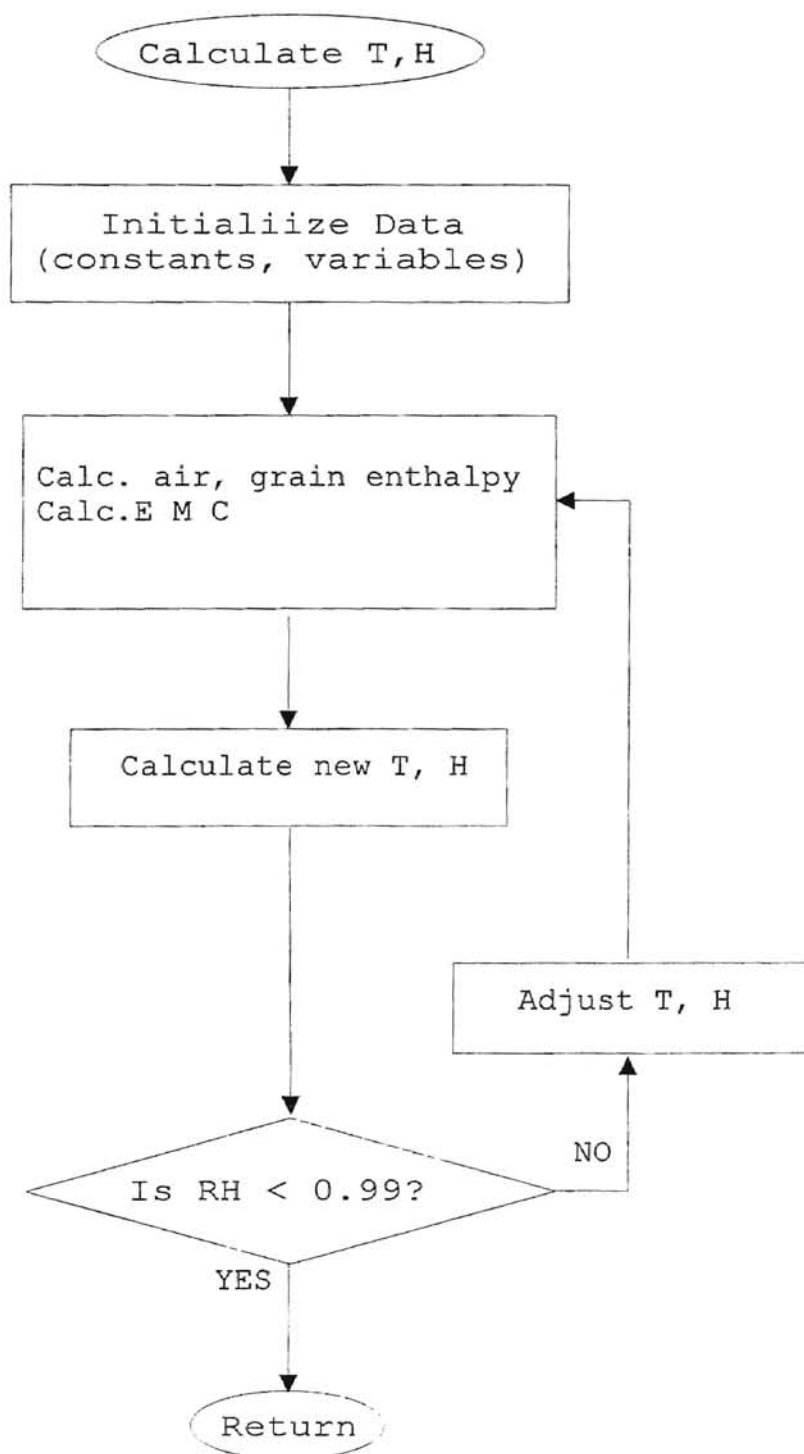


Figure 10. Flow Chart of T, H Calculation Subroutine

Pfost et al. (1976) stated that the standard error of $\text{emc} \sim 0.0071$. Table 1 shows results of equation (24) within the temperature range of 40 °F to 120 °F.

Equation (23) was the computer model to calculate equilibrium relative humidity(ERH), and equation (24) was the computer model to calculate equilibrium moisture content(emc). The models were coded in C programming language. The subroutine programs of both models are 'ERH' and 'EMC' which can be shown as follows:

```
double ERH(double mdb, double TF)
{
    /******
    /* This sub. calc. equilibrium RH in decimal unit */
    /* RH      : Relative Humidity [decimal unit]      */
    /* TF      : Temp, deg F (dry bulb)                */
    /* TC      : Temp, deg C (dry bulb)                */
    /* mdb     : EMC dry basis [decimal unit]          */
    /*          Use only for red wheat                 */
    /******
    double TC,RH;

    TC = (TF-32.)/1.8;
    RH = 1.- exp(-2.3008e-5*(TC+55.815)\
*pow(mdb*100.,2.2857));
    return(RH);
}

double EMC(double H, double T)
{
    /******
    /* This sub. return EMC, decimal unit db          */
    /* H       : humidity ratio, lb/lb dry air         */
    /* T       : Temp, deg F (dry bulb)                */
    /* TC      : Temp, deg C (dry bulb)                */
    /* mdb     : EMC % dry basis                       */
    /* Rh      : Relative Humidity [decimal unit]      */
    /*          Use only for red wheat                 */
    /******
    double mdb,Rh,TC;

    Rh=RH(H,T);
    TC= (T-32.)/1.8;
    mdb =pow(log(1.-Rh)/(-2.3008e-5*(TC+55.815)), (1./2.2857));
    return (mdb*.01);
}
```

TABLE I
EQUILIBRIUM MOISTURE CONTENT OF RED WHEAT, %db

Temp	F	40	50	60	70	80	90	100	120
RH[%]	C	4.4	10.0	15.6	21.1	26.7	32.2	37.8	48.9
5		4.9	4.7	4.5	4.4	4.2	4.1	4.0	3.8
10		6.7	6.4	6.2	6.0	5.8	5.6	5.5	5.2
15		8.0	7.7	7.5	7.2	7.0	6.8	6.6	6.3
20		9.2	8.9	8.6	8.3	8.0	7.8	7.6	7.3
25		10.3	9.9	9.6	9.3	9.0	8.7	8.5	8.1
30		11.3	10.9	10.5	10.2	9.9	9.6	9.4	8.9
35		12.3	11.8	11.4	11.1	10.7	10.4	10.2	9.7
40		13.3	12.8	12.3	11.9	11.6	11.2	10.9	10.4
45		14.2	13.7	13.2	12.8	12.4	12.0	11.7	11.2
50		15.2	14.6	14.1	13.6	13.2	12.8	12.5	11.9
55		16.1	15.5	15.0	14.5	14.1	13.7	13.3	12.7
60		17.1	16.5	15.9	15.4	14.9	14.5	14.1	13.5
65		18.2	17.5	16.9	16.3	15.8	15.4	15.0	14.3
70		19.3	18.6	17.9	17.3	16.8	16.4	15.9	15.2
75		20.5	19.8	19.1	18.5	17.9	17.4	16.9	16.1
80		21.9	21.1	20.4	19.7	19.1	18.6	18.1	17.2
85		23.6	22.7	21.9	21.2	20.5	20.0	19.4	18.5
90		25.6	24.7	23.8	23.0	22.3	21.7	21.1	20.1
95		28.8	27.7	26.7	25.9	25.1	24.4	23.7	22.6

Equilibrium Moisture Content of Red Wheat [%db]

Note: Calculated from equation (24)

Enthalpy of Water Vaporization Model (hfg)

This model calculates enthalpy of water vaporization (hfg) from a given temperature. The model is from Thermodynamic Properties of Water at Saturation, ASHRAE 1985 Fundamental Handbook. Linear interpolation of latent heat of vaporization hfg [Btu/lb] and temperature [°F] were calculated for the model from a temperature of 32°F to 120°F.

$$\text{hfg[Btu/lb]} = 1093.3136 - 0.56761364 * T[^\circ\text{F}] \quad (25)$$

The hfg model was computer coded to the subroutine program which can be shown as follows;

```
double hfg(double TF)
{
    double BTU;

    BTU = 1093.3136 - 0.56761364*TF;
    return(BTU)
}
```

Vapor Pressure Model

The model is adapted from Thermodynamic Properties of Water at Saturation, ASHRAE 1985 Fundamental Handbook. The saturation pressure over liquid water for the temperature range of 32 °F to 392 °F is given by:

$$\ln(\text{Pvs}) = A/T + B + CT + DT^2 + ET^3 + F\ln(T) \quad (26)$$

where

Pvs : Saturation vapor pressure, psia

T : Absolute temp., °R (°F + 459.67)
 A = -10440.4, B = -11.2946669
 C = -0.02700133, D = 0.1289706e-4
 E = -0.2478068e-8, F = 6.5459673

The computer code of the model is shown as follows;

```

double Pvs(double T)
{
    double TRK;

    TRK = T + 459.67;

    return (exp(-10440.4/TRK -11.2946669 -0.02700133*TRK
        +1.289706e-5*TRK*TRK -2.478068e-9*TRK*TRK*TRK
        +6.5459673*log(TRK)));
}
  
```

Relative Humidity Model (RH)

From basic thermodynamics, absolute humidity (H) is defined as the ratio of the mass of water vapor to the mass of dry air contained in the sample ($H = M_w / M_a$). M_w and M_a are in gas form so that they can be changed in mole fraction form by using their molecular mass ratio.

$$H = 0.62198 * \frac{\text{mole fraction of vapor}}{\text{mole fraction of air}}$$

0.62198 is the ratio of molecular mass of vapor (18.01534) to molecular mass of air (28.9645). Because vapor pressure of any gases relate directly to their mole fraction, absolute humidity will be proportional to vapor pressure ratio.

let Pv = Vapor pressure

and Patm = Atmospheric pressure

$$H = 0.62198 * \frac{P_v}{P_{air}} \quad (27)$$

$$H = 0.62198 * \frac{P_v}{(P_{atm} - P_v)} \quad (28)$$

$$\text{Hence } P_v = \frac{H * P_{atm}}{(0.62198 + H)} \quad (29)$$

So, relative humidity (RH) can be derived from the ratio of vapor pressure (Pv) to saturated vapor pressure (Ps), $RH = P_v / P_{vs}$, for a given temperature (T) and humidity ratio (H). H can be found by using equation (28) and a given RH and temperature.

Computer coding of the model can be shown as follows:

```
double RH(double H, double T)
```

```
{
  /*****
  /* This sub. calc. Relative Humid. [decimal] */
  /* from Humid. ratio and Temp [deg F] */
  /* Pv : vapor pressure */
  /* Pvs : sat. vapor pressure */
  /*****

  double P, Pv, Ps, RH;
    P = Pabs;
    Ps = Pvs(T);
    Pv = H*P/(0.62198+H);
    RH = Pv/Ps;
  return (RH);
}
```

```
double H(double RH, double T)
```

```
{
  /*****
  /* This sub. calc. Humidity Ratio [lb/lb] */
  /* from Relative Humidity and Temp [deg F] */
  /* Patm : atmospheric pressure [psia] */
  /* Ps : sat. vapor pressure [psia] */
  /*****
```

```
double H,P,Pv;  
    P=Patm;  
    Pv = Pvs(T)*RH;  
    H =(0.62198)*Pv/(P-Pv);  
    return(H);  
}
```

CHAPTER IV

RESULTS AND DISCUSSIONS

A calculation program was developed based on mathematical models (presented in Chapter III). A computer simulation program was then written, based on a calculation program in C computer language and compiled by a C-compiler (Turbo C 2.0 version). Aeration simulations were run by the computer simulation program, and the results, grain temperatures and moisture contents, were obtained. The simulations were made utilizing the same initial parameters (temperature, humidity, and moisture content) and airflow rates which were used in the experiment. The results of the simulation, grain temperature, and moisture content, were then graphically compared with the experimental results.

Experimental aeration was tested and the results obtained by Epperly (1989). The experiment can be described as follows. Aeration was tested by using a 6-ft diameter bin filled to a height of 9 ft with hard red winter wheat. Six different airflow rates(Q), from 0.67 to 10.72 l/(sm³), were chosen for testing. At each airflow rate, grain

temperatures and final moisture contents were recorded versus time by using a data logger machine.

Grain Temperatures

The computer simulation results (Appendix B) were printed at 1 hr and 5 hr time periods. Time intervals that were consistent with the time intervals use by Epperly in his experimental testing are shown in Table II.

TABLE II

EFFECT OF TIME, AIRFLOW RATE, AND BED POSITION
ON GRAIN TEMPERATURE DURING AERATION AS
PREDICTED BY THE SIMULATION MODEL

Airflow rate (Q), Litre/(sm³)

Temperature, °C

X/L : Location of grain over total height of grain, ft/ft

X/L	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
<hr/>											
Q=0.67											
25h	14.4	23.6	33.2	36.4	37.1	37.2	37.2	37.2	37.2	37.2	37.2
50h	14.4	14.7	23.9	31.2	35.3	36.7	37.1	37.2	37.2	37.2	37.2
150h	14.4	14.4	14.5	14.5	15.3	15.7	21.4	26.4	31.4	34.3	36.0
Q=1.34											
10h	14.4	26.8	35.6	37.9	38.3	38.3	38.3	38.3	38.3	38.3	38.3
25h	14.4	14.7	24.1	32.0	36.3	37.8	38.2	38.3	38.3	38.3	38.3
55h	14.4	14.4	14.4	14.4	19.4	25.7	31.8	35.4	37.2	38.0	38.2
100h	14.4	14.4	14.4	14.4	14.5	14.5	14.9	14.9	19.3	23.8	29.9
Q=2.68											
10h	14.4	18.8	27.8	33.9	36.4	37.0	37.2	37.2	37.2	37.2	37.2
20h	14.4	15.4	17.1	22.0	28.7	33.3	35.8	36.8	37.1	37.2	37.2
40h	14.4	14.9	14.9	15.9	15.9	18.0	20.7	24.4	29.3	32.8	35.2
70h	14.4	14.6	14.6	15.1	15.1	15.9	15.9	16.3	17.3	17.3	20.2

(Table II concluded)

X/L	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Q=5.36											
2h	18.3	29.5	35.3	36.5	36.6	36.7	36.7	36.7	36.7	36.7	36.7
6h	18.3	19.3	26.4	32.2	35.3	36.3	36.6	36.7	36.7	36.7	36.7
12h	18.3	18.3	18.3	20.0	25.4	30.3	33.9	35.6	36.3	36.6	36.6
24h	18.3	18.3	18.3	18.3	18.3	18.3	18.7	19.6	23.5	27.2	31.4
Q=8.04											
2h	17.8	26.5	34.9	37.6	38.2	38.3	38.3	38.3	38.3	38.3	38.3
5h	17.8	18.0	23.0	29.9	35.0	37.2	38.1	38.3	38.3	38.3	38.3
12h	17.8	17.8	17.8	17.8	18.1	20.0	24.7	29.5	33.7	36.1	37.4
20h	17.8	17.8	17.3	17.8	17.8	17.8	17.8	17.8	19.1	19.1	24.8
Q=10.7											
1h	18.9	28.7	33.8	34.8	35.0	35.0	35.0	35.0	35.0	35.0	35.0
2h	18.9	23.3	30.4	33.7	34.7	35.0	35.0	35.0	35.0	35.0	35.0
4h	18.9	18.9	22.3	27.5	31.8	33.9	34.7	34.9	35.0	35.0	35.0
8h	18.9	18.9	18.9	18.9	20.3	23.1	27.5	30.9	33.2	34.2	34.7
14h	18.9	18.9	18.9	18.9	18.9	18.9	19.0	19.0	20.4	21.5	26.3

Data from simulation results (Table II) and experimental results (Appendix A) were then plotted and shown in graphical illustrations (Figure 11 through 16). Information given in Figures 11 through 16 shows the graphical comparison of grain temperature between computer prediction results and experimental results at the different airflow rates.

Information in Figure 11 shows grain temperature profiles from computer simulation and actual measurements at $Q = 0.67 \text{ l/(sm}^3\text{)}$. The initial grain temperature was 37°C , and the inlet air temperature was 14°C . In Figure 11,

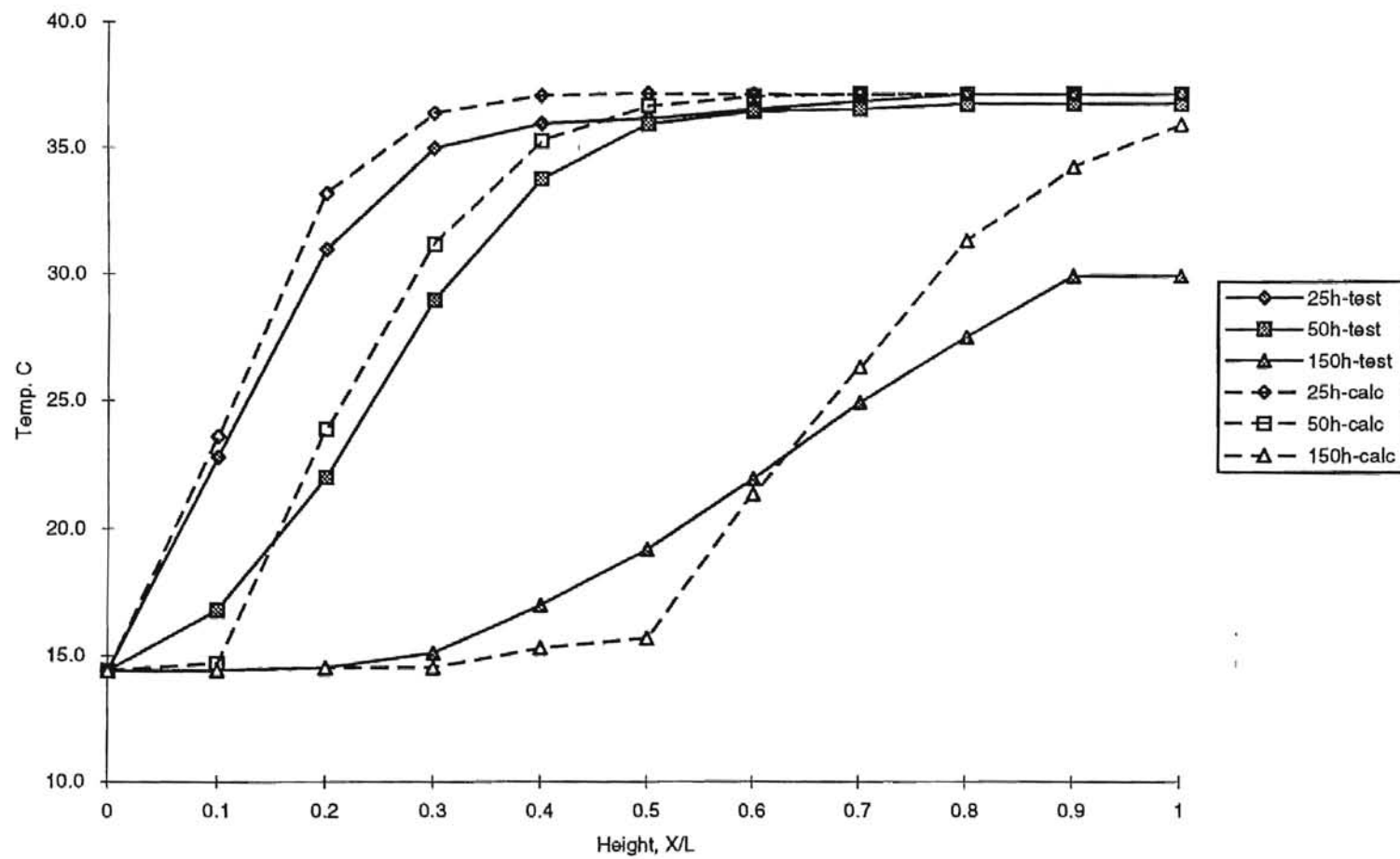


Figure 11. Predicted and Measured Grain Temperature Profiles at $Q = 0.67 \text{ l}/(\text{sm}^3)$

temperature profiles of the simulation are shown at duration of 25, 50, and 150 hours.

At the first 25-hr profile time period, simulation results (grain temperatures) were a little higher than measured temperatures throughout the bin. From the next 25-hr time period (50-hr profile), most of the calculation temperatures were higher than measured temperatures, except at $X/L = 0.1$, where the calculation temperature was lower than measured temperatures. At the 150-hr profile, calculated temperatures at the bottom to the middle of bin were less than measured temperatures.

Data in Figure 12 shows the results of grain temperature profiles at $Q = 1.34 \text{ l}/(\text{sm}^3)$. Initial grain temperature was 38°C , and inlet air temperature was 14°C . Simulation time was chosen at the 10-hr, 25-hr, 55-hr, and 100-hr intervals. At the 10-hr profile, both grain temperatures, calculated and measured, were closer than the others. However, at the 25-hr, 55-hr, and 100-hr intervals, the difference between calculated and measured temperature was much wider than that at the 10-hr profile.

Information in Figure 13 shows the simulation results at $Q = 2.68 \text{ l}/(\text{sm}^3)$. Initial grain temperature was 37°C and inlet air temperature was 14°C . Simulation time was chosen at 10-hr, 20-hr, 40-hr, and 70-hr intervals. At the time

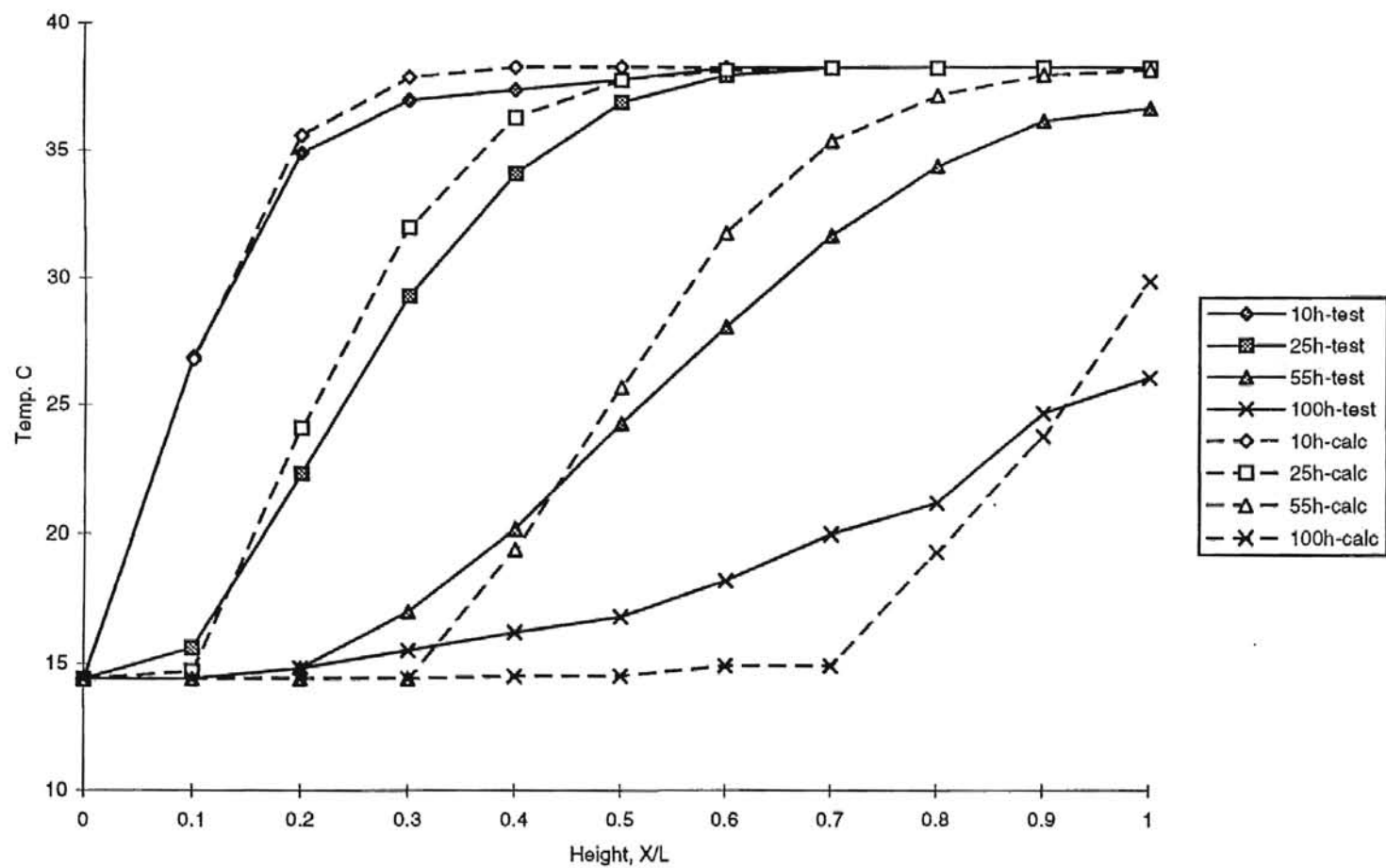


Figure 12. Predicted and Measured Grain Temperature Profiles at $Q = 1.34 \text{ l/(sm}^3\text{)}$

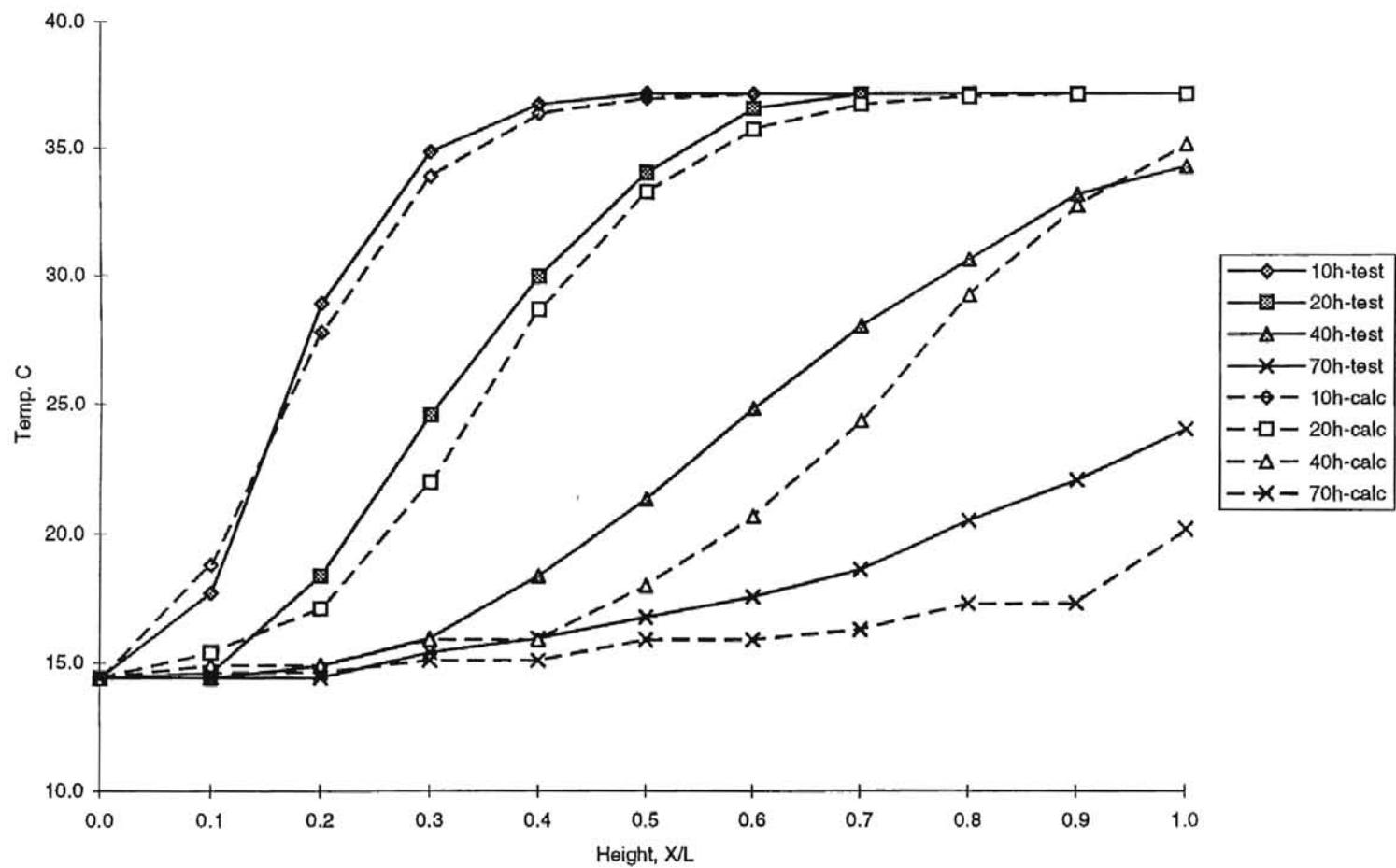


Figure 13. Predicted and Measured Grain Temperature Profiles at $Q = 2.68 \text{ l/(sm}^3\text{)}$

periods of 10 hr and 20 hr, predicted temperatures were very close to the actual ones. However, at the 40-hr and 70-hr intervals, both calculated temperature profiles were lower than measured temperatures.

Figures 14 and 15 show grain temperature profiles of simulation and actual measurement at $Q = 5.36 \text{ l/(sm}^3\text{)}$ and $8.04 \text{ l/(sm}^3\text{)}$. Initial grain temperature was 38°C , and inlet air temperature was 18°C . Periods of prediction at 2-hr, 6-hr, 12-hr, and 24-hr intervals were chosen for $Q = 5.36 \text{ l/(sm}^3\text{)}$. Two-hr, 5-hr, 12-hr, and 20-hr intervals were chosen for $Q = 8.04 \text{ l/(sm}^3\text{)}$. Both simulations show more difference in calculated temperature and measured temperature than those of previous simulations.

The final simulation set airflow rate at $10.7 \text{ l/(sm}^3\text{)}$. Initial grain temperature was 35°C and inlet air temperature was 19°C . Grain temperatures were plotted and shown in Figure 16 at time periods of 1 hr, 2 hr, 4 hr, 8 hr, and 14 hr. From the beginning of simulation to the 1-hr period, results of temperature calculation coincided with measured temperatures. At the 2-hr period, temperature calculation differed more than at the 1-hr period. As simulation time continued (at 4-hr and 8-hr periods), temperature calculation differed even more. However, error of temperature calculation tended to decrease as simulation

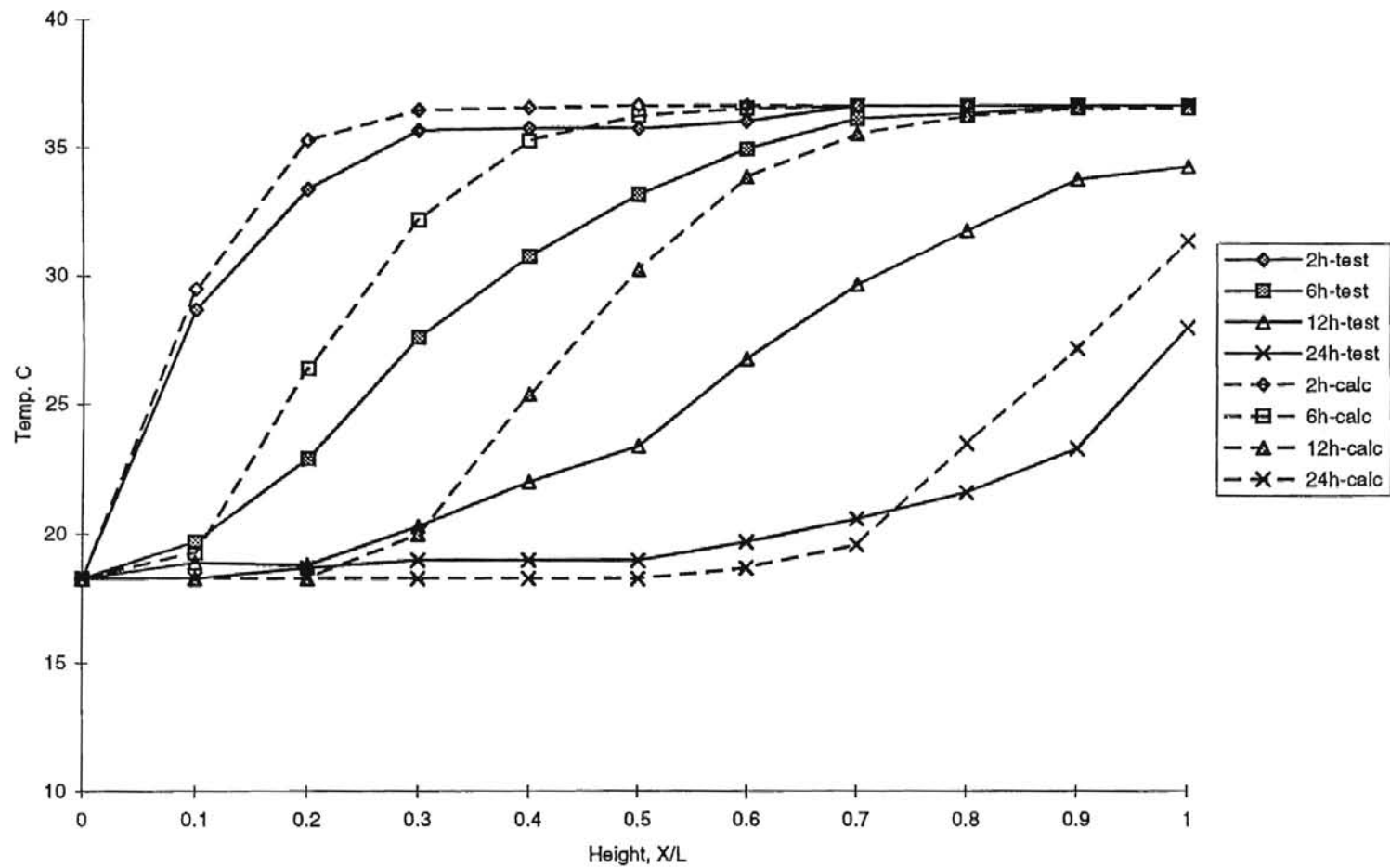


Figure 14. Predicted and Measured Grain Temperature Profiles at $Q = 5.36 \text{ l/(sm}^3\text{)}$

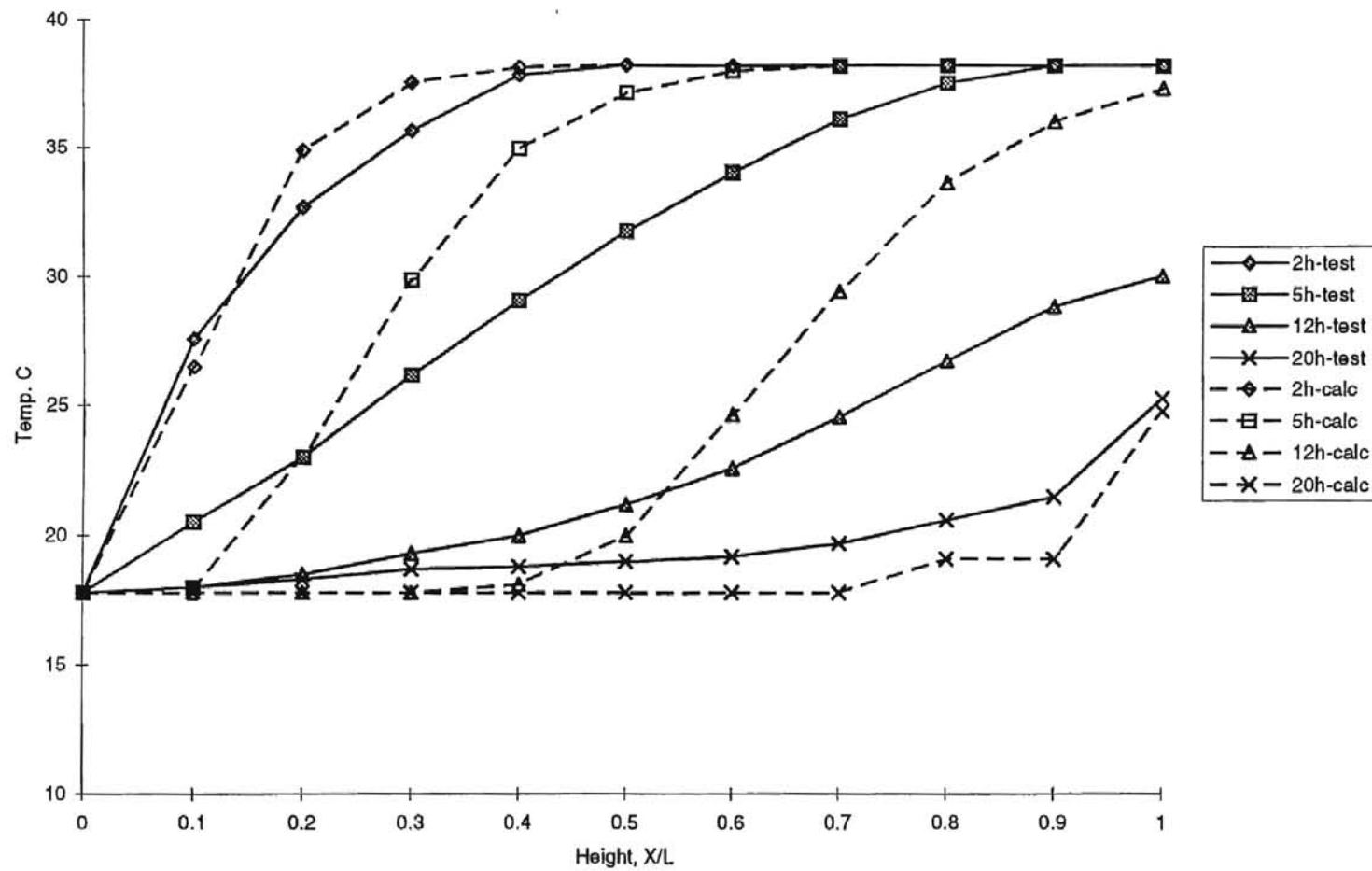


Figure 15. Predicted and Measured Grain Temperature Profiles at $Q = 8.04 \text{ l/(sm}^3\text{)}$

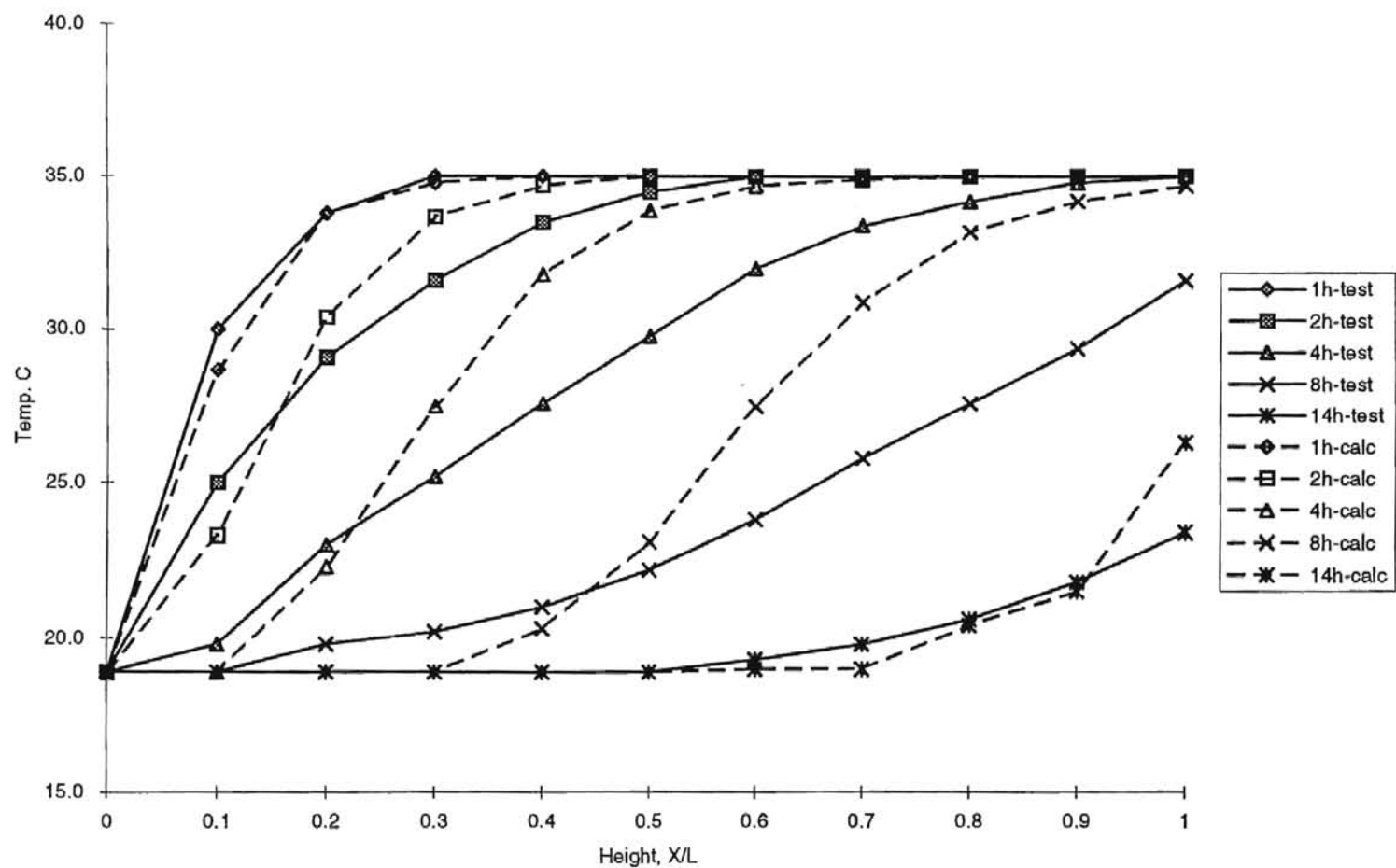


Figure 16. Predicted and Measured Grain Temperature Profiles at $Q = 10.7 \text{ l/(sm}^3\text{)}$

time reached the final 14-hr period of aeration.

To examine whether predicted temperatures were correlated with measured temperatures, a scatter plot was developed for each airflow rate, and linear regression of data was calculated and analyzed. Figures 17 and 18 show samples of scatter plots at airflow rates 0.67 and 1.34 $l/(sm^3)$. Table III shows a summary of correlation of predicted and measured temperatures at various airflow rates. Table IV shows a summary of analysis of variance of predicted and measured temperatures.

TABLE III
CORRELATION OF PREDICTED AND MEASURED TEMPERATURES
AT VARIOUS AIRFLOW RATES

Q, $l/(sm^3)$	0.67	1.34	2.68	5.36	8.04	10.72
Correlation, R	0.9812	0.9879	0.9868	0.9576	0.9563	0.9670
R^2	0.9627	0.9760	0.9738	0.9170	0.9146	0.9350
Standard error	1.7665	1.4850	1.6895	2.2628	2.6947	1.7709
observations	30	40	40	40	40	50

Note: R^2 is coefficient of determination.

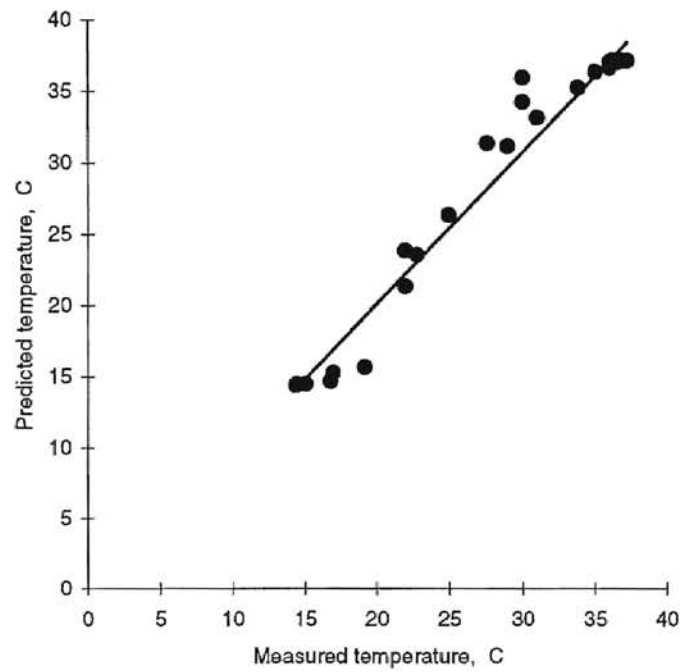


Figure 17. Scatter Plot of Predicted Temperature at $Q = 0.67 \text{ l}/(\text{sm}^3)$

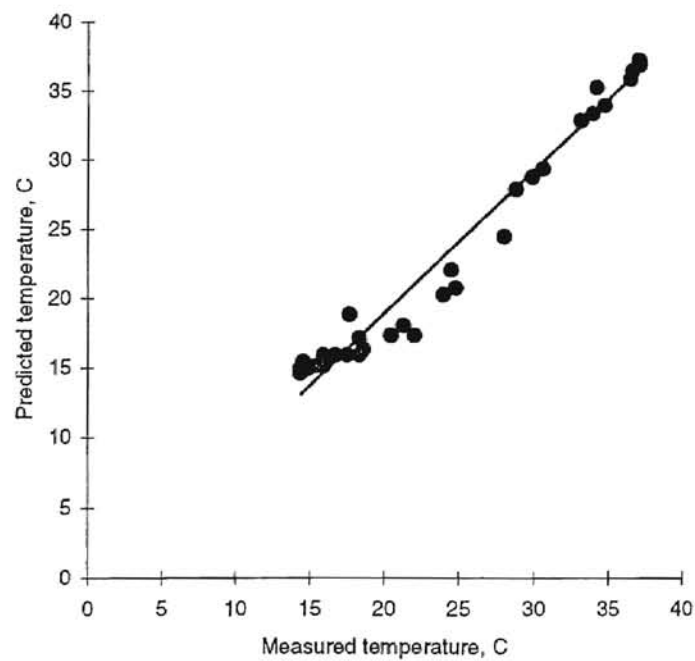


Figure 18. Scatter Plot of Predicted Temperature at $Q = 2.68 \text{ l}/(\text{sm}^3)$

TABLE IV

ANOVA OF PREDICTED AND MEASURED TEMPERATURES
AT VARIOUS AIRFLOW RATESQ = 0.67 l/(sm³)

	df	SS	MS	F
Regression	1	2256.664919	2256.664919	723.1403653
Residual	28	87.37808142	3.120645765	
Total	29	2344.043		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-1.150522028	1.208540523	-0.951992926	0.349246807	-3.626107845	1.32506379
X Variable 1	1.065323878	0.039615976	26.89126931	1.52157E-21	0.984174139	1.146473618

Q = 1.34 l/(sm³)

	df	SS	MS	F
Regression	1	4023.907407	4023.907407	1409.767806
Residual	38	108.463593	2.854305078	
Total	39	4132.371		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-2.233366769	0.866464821	-2.577561968	0.013953733	-3.987433157	0.479300381
X Variable 1	1.085336376	0.028906171	37.54687478	1.19477E-31	1.026818891	1.143853862

Q = 2.68 l/(sm³)

	df	SS	MS	F
Regression	1	3406.724697	3406.724697	1544.828348
Residual	38	83.79930278	2.20524481	
Total	39	3490.524		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-1.728609405	0.734365466	-2.353881665	0.023851483	-3.215254619	-0.24196419
X Variable 1	1.027675943	0.026146651	39.30430445	2.19203E-32	0.974744813	1.080607073

Q = 5.36 l/(sm³)

	df	SS	MS	F
Regression	1	2152.027671	2152.027671	420.2934324
Residual	38	194.5713285	5.12029812	
Total	39	2346.599		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	0.639041533	1.469320728	0.434923105	0.666078372	-2.335442878	3.613525943
X Variable 1	1.030091087	0.050245749	20.5010593	3.81215E-22	0.928373882	1.131808293

(Table IV concluded)

Q = 8.04 l/(sm³)

	df	SS	MS	F
Regression	1	2953.955315	2953.955315	406.7858881
Residual	38	275.9444348	7.261695652	
Total	39	3229.89975		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-1.980104042	1.572422727	-1.259269538	0.215613464	-5.163307545	1.203099461
X Variable 1	1.101880673	0.054632569	20.16893374	6.73899E-22	0.991282814	1.212478531

Q = 10.72 l/(sm³)

	df	SS	MS	F
Regression	1	2166.111281	2166.111281	690.6833361
Residual	48	150.5369191	3.136185814	
Total	49	2316.6482		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	-0.00320229	1.127715081	-0.002839627	0.997746078	-2.270624099	2.264219519
X Variable 1	1.026908397	0.039074391	26.28085494	3.80046E-30	0.948344115	1.105472679

Information in Table III, shows a very strong correlation between predicted and measured temperature all airflow rates (greater than 95%). At low airflow rates (0.67, 1.34, and 2.68 l/(sm³)), the degrees of correlation, 98.12%, 98.79% and 98.68%, are a little more than that of higher airflow rates, 95.76%, 95.63% and 96.70%.

Hypothesis testing of correlation can be made by examining each of the F-values included in Table IV. All F-values are much more than $F_{0.01,1,28}$ (7.64) which means there is a high confidence in correlation of predicted and measured temperatures.

Information presented in Table IV also shows the deviation of prediction by the slope of regression. There is no deviation, if the slope is 1.0. Slope of regression can be found in Table IV, in the Coefficients column and X Variable row. The range of slopes is 1.0269 to 1.102.

Accuracy of the temperature prediction can be determined by observing the temperature error; difference between prediction and measurement. At each prediction, average absolute error was calculated from summation of grain temperature difference (at the same time period and locations) between simulation results and testing results at various airflow rate(Q) conditions. A summary of the grain temperature error at various airflow rates is shown in Table V. Graphical comparisons of Table V are shown in Figures 19 and 20.

TABLE V

AVERAGE ABSOLUTE ERROR OF TEMPERATURE PREDICTION AT
VARIOUS TIME PERIODS AND AIRFLOW RATES

Unit : Degree Celsius

Q, l/(sm ³)	0.67	1.34	2.68	5.36	8.04	10.72
Profile #1	.74	.31	.37	.58	.55	.15
Profile #2	1.08	.87	.81	1.85	2.60	.68
Profile #3	2.19	1.87	1.70	3.43	3.39	1.74
Profile #4		2.05	1.83	1.37	1.15	2.61
Profile #5						.45
Maximum	2.19	2.05	1.83	3.43	3.39	2.61

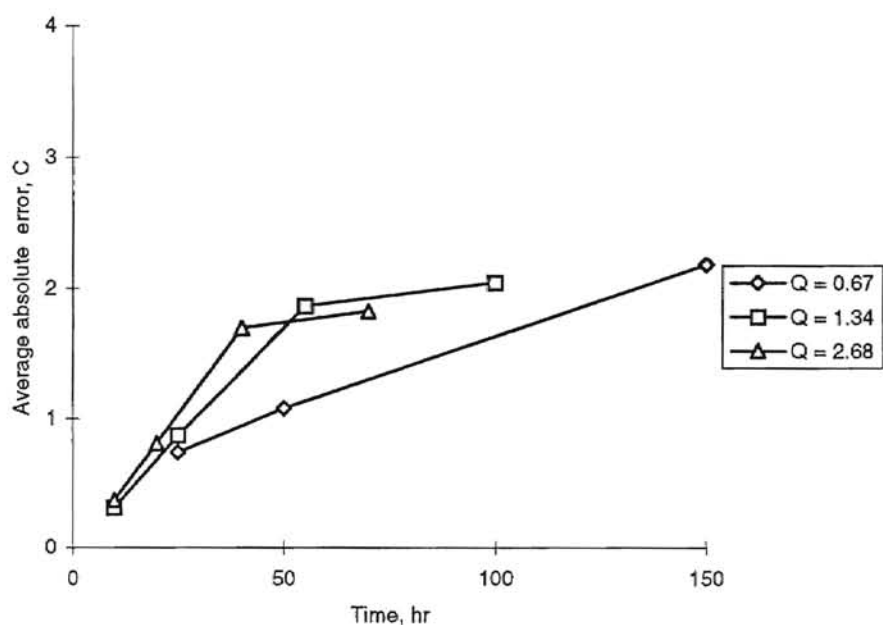


Figure 19. Plotting of Average Absolute Error Over Different Time Periods at $Q = 0.67, 1.34$ and $2.68 \text{ l/(sm}^3\text{)}$

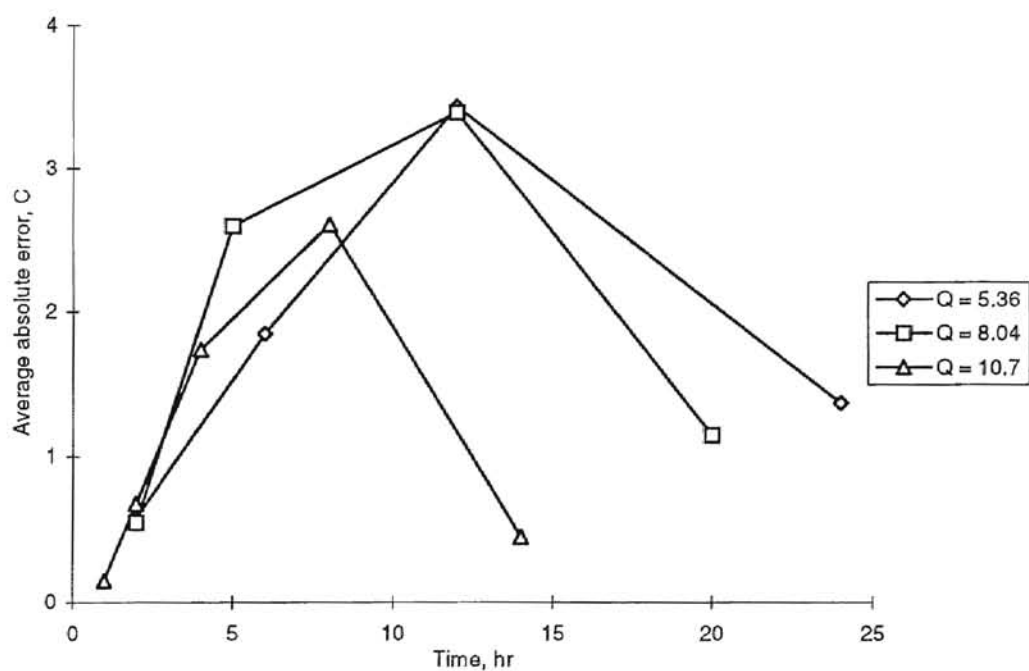


Figure 20. Plotting of Average Absolute Error Over Different Time Periods at $Q = 5.36, 8.04$ and $10.7 \text{ l/(sm}^3\text{)}$

From information presented in Table V, it can be concluded:

- Maximum average absolute error occurs at the middle of simulation and tends to have more error at the higher airflow rate. At high airflow rate, heat and mass transfer rates between the grain kernel and air will be high enough to cause error in the initial and boundary conditions of equilibrium between grain and air. Additionally, the higher airflow rate causes an increase in the convective heat transfer coefficient causing the Biot number to increase.

- When aeration time is close to the final stage, for example at $Q = 5.36, 8.04, \text{ and } 10.7 \text{ l}/(\text{sm}^3)$; average absolute errors decrease to $1.37, 1.15 \text{ and } 0.45^\circ\text{C}$

- At every airflow rate simulation, summation of error is increased as the simulation time continues until approximate by the middle of the simulation. After that, the error trends to decrease as the simulation time approaches the final state; therefore, prediction time and temperatures at the final state of simulation will have sufficient accuracy to predict the aeration time needed for hard red winter wheat.

Grain Moisture Contents

Grain moisture contents were measured at the end of the aeration experiment. The measured grain moisture content and prediction results are shown in Table VI. The difference from both results also are shown in Table VI.

Information presented in Table VI is plotted in Figures 21 through 23 and shows the graphical comparison of grain moisture content between the computer prediction results and the experimental results at different airflow rates. Three airflow rates (0.67 , 2.68 and $8.04 \text{ l/(sm}^3\text{)}$) were chosen to compare with the calculation results.

Information presented in Figure 21 shows the moisture content profile of simulation at $Q = 0.67 \text{ l/(sm}^3\text{)}$. The profile shows that the final moisture content was 12.2 \%wb and the average error was 0.62 \%wb (Table VI).

Information in Figure 22, shows the final moisture content result at $Q = 2.68 \text{ l/(sm}^3\text{)}$. The result was 12.2\%wb .

The average error is 0.64 \%wb as shown in Table VI. At the next simulation, Figure 23 ($Q = 8.04 \text{ l/sm}^3$), the prediction of final moisture content is a little less than the actual measurement, so the error is higher than those of lower airflow rate. The final moisture content was 10.3 \%wb and the average error was 1.88 \%wb .

TABLE VI

PREDICTED AND MEASURED FINAL MOISTURE CONTENTS
AT DIFFERENT AIRFLOW RATES BY LOCATION

Q : Airflow rate, Litre/(sm³)

Moisture content, %wb

L(ft)	Q = 0.67			Q = 2.68			Q = 8.04		
	test	calc	diff	test	calc	diff	test	calc	diff
0.5	12.81	12.20	0.61	13.00	12.20	0.80	12.00	10.31	1.69
1.0	13.13	12.20	0.93	12.67	12.20	0.47	12.11	10.31	1.80
1.5	13.34	12.20	1.14	12.77	12.20	0.57	12.29	10.31	1.98
2.0	13.03	12.20	0.83	11.83	12.20	0.37	12.16	10.31	1.85
2.5	12.93	12.20	0.73	11.98	12.20	0.22	12.27	10.31	1.96
3.0	12.73	12.20	0.53	11.80	12.20	0.40	12.42	10.31	2.11
3.5	12.66	12.20	0.42	11.91	12.20	0.29	12.46	10.31	2.15
4.0	12.42	12.20	0.22	11.72	12.20	0.48	12.50	10.31	2.19
4.5	12.11	12.20	0.09	11.85	12.20	0.35	12.37	10.31	2.06
5.0	11.92	12.20	0.28	11.44	12.20	0.76	12.35	10.31	2.04
5.5	11.84	12.20	0.36	11.38	12.20	0.82	12.30	10.31	1.99
6.0	11.75	12.28	0.53	11.36	12.28	0.92	12.22	10.31	1.91
6.5	11.70	12.28	0.58	11.25	12.28	1.03	12.18	10.47	1.71
7.0	11.75	12.28	0.53	11.24	12.28	1.04	12.17	10.47	1.70
7.5	11.68	12.28	0.60	11.29	12.28	0.99	12.25	10.47	1.78
8.0	11.34	12.28	0.94	11.49	12.28	0.79	12.12	10.47	1.65
8.5	11.03	12.28	1.25	11.74	12.28	0.54	12.02	10.47	1.55
Average			0.62			0.64			1.88

Note: Testing data from Epperly (1989)

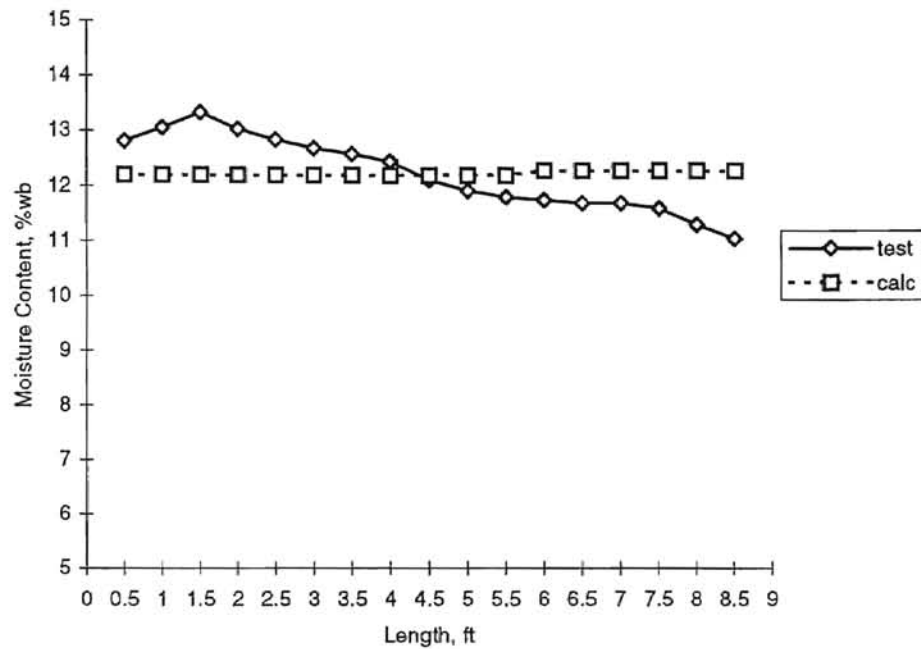


Figure 21. Predicted and Measured Final Moisture Content at $Q = 0.67 \text{ l/(sm}^3\text{)}$

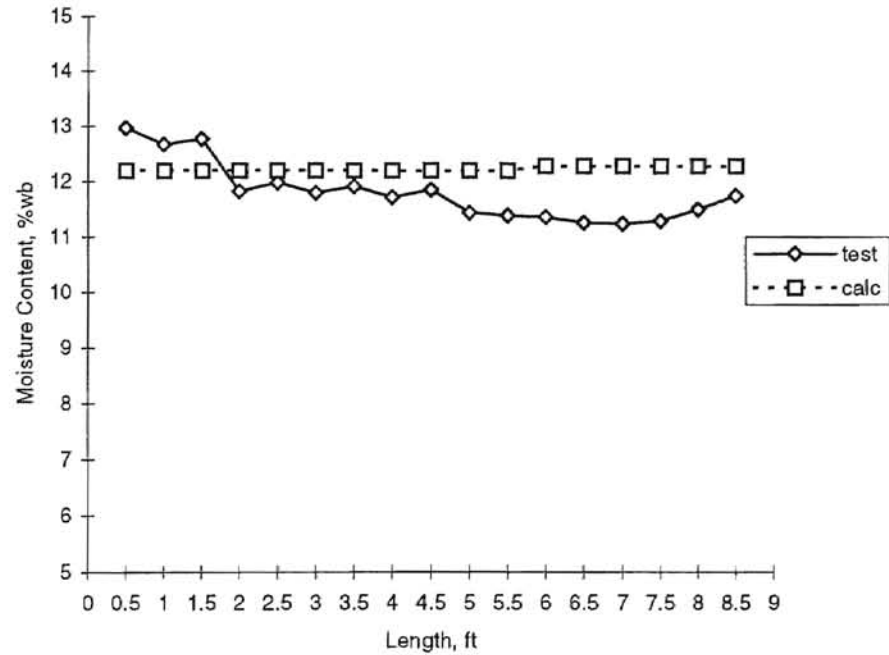


Figure 22. Predicted and Measured Final Moisture Content at $Q = 2.68 \text{ l/(sm}^3\text{)}$

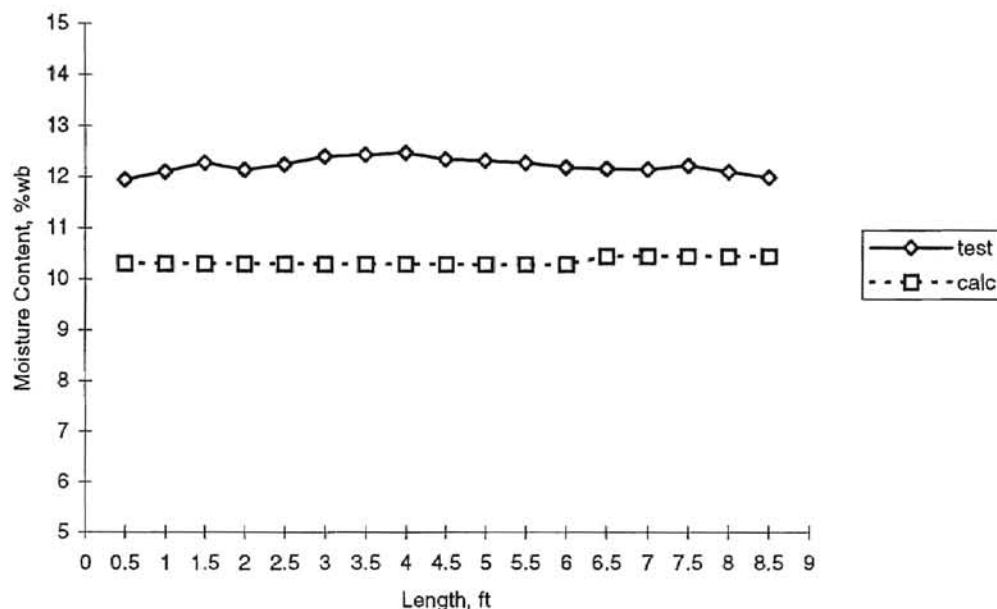


Figure 23. Predicted and Measured Final Moisture Content at $Q = 8.04 \text{ l/(sm}^3\text{)}$

Figure 24 shows the average absolute error of predicted moisture content at various airflow rates. The error tends to increase when airflow rate is increased.

Sample scatter plot of predicted and measured moisture contents at $Q = 0.67 \text{ l/(sm}^3\text{)}$ is shown in Figure 25.

Correlation of predicted and measured moisture content was calculated and shown in Table VII. Information presented in Table VIII, shows analysis of variance.

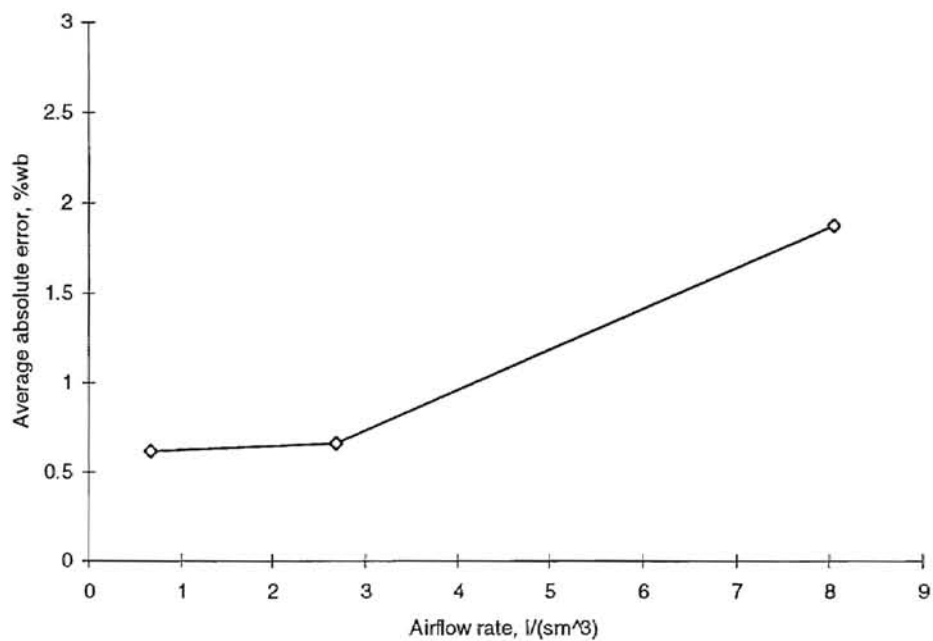


Figure 24. Average Absolute Error of Final Moisture Contents by Various Airflow Rates at $Q = 0.67, 2.68$ and $8.04 \text{ l/(sm}^3\text{)}$

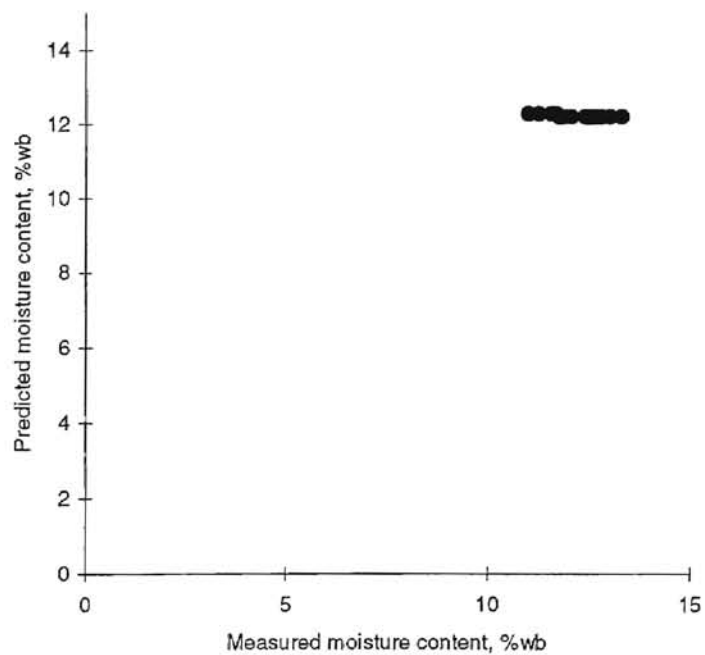


Figure 25. Scatter Plot of Predicted Moisture Content at $Q = 0.67 \text{ l/(sm}^3\text{)}$

TABLE VII
CORRELATION OF PREDICTED AND MEASURED
FINAL MOISTURE CONTENTS

Q, l/(sm ³)	0.67	2.68	8.04
Correlation, R	0.7696	0.5619	0.4253
R ²	0.5924	0.3160	0.1809
Standard error	0.0252	0.0327	0.0690
observations	17	17	17

Note: R² is coefficient of determination.

TABLE VIII
ANOVA OF PREDICTED AND MEASURED FINAL MOISTURE
CONTENTS AT VARIOUS AIRFLOW RATES

Unit : Q , l/(sm³)

At Q = 0.67

	df	SS	MS	F
Regression	1	0.01388833	0.01388833	21.7979359
Residual	15	0.00955709	0.00063714	
Total	16	0.02344542		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	12.7548382	0.11263258	113.242881	2.0587E-23	12.5147674	12.994909
X Variable 1	-0.04297686	0.00920507	-4.66882596	0.00030279	-0.06259701	-0.02335671

(Table VIII concluded)

At $Q = 2.68$

	df	SS	MS	F
Regression	1	0.00740162	0.00740162	6.92007323
Residual	15	0.0160438	0.00106959	
Total	16	0.02344542		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	12.7021863	0.17976607	70.6595313	2.4021E-20	12.3190237	13.0853488
X Variable 1	-0.04001738	0.01521224	-2.63060321	0.01890975	-0.07244153	-0.00759323

At $Q = 8.04$

	df	SS	MS	F
Regression	1	0.01576041	0.01576041	3.3132233
Residual	15	0.07135232	0.00475682	
Total	16	0.08711274		

	Coefficients	Standard Error	t Stat	P-value	Lower 95%	Upper 95%
Intercept	12.8961139	1.39387754	9.25197051	1.3759E-07	9.92513243	15.8670954
X Variable 1	-0.20720069	0.11383239	-1.82022617	0.08873459	-0.44982884	0.03542745

From information presented in Figure 25 and Table VII, there is a fair degree of correlation, 77% at $Q = 0.67$ $l/(sm^3)$, and decreases to weak correlation when the airflow rate is increased, 56% at $Q = 2.68$ $l/(sm^3)$ and 42% at $Q = 8.04$ $l/(sm^3)$. The analysis of variance, Table VIII, also shows weak correlation, because the regression slopes (-0.04, -0.04 and -0.21) are low approaching the value of zero.

The explanation is that in the practical situation, physical properties of grain and moisture content may not match the initial assumption. For example, no gradient of

temperature and moisture content of a bin cross section, and bin wall is in adiabatic condition. These results also show the effect of airflow rates leading to lower correlation and larger average absolute error at high airflow rates.

The predicted and measured results were not identical, but at the low airflow rates, average absolute errors were within 1%, 0.62% at $0.67 \text{ l}/(\text{sm}^3)$, and 0.64% at $2.68 \text{ l}/(\text{sm}^3)$. This result suggests that the simulation model may be used for moisture content prediction where 1% moisture content accuracy is acceptable.

To improve accuracy of calculation, a number of node (20) were applied, however, the error of prediction were not significantly different from the present results. A longer time step (2x) may be used to reduce simulation time, in case of aeration with very low airflow rate.

CHAPTER VI

CONCLUSIONS

Information presented in Chapter I shows that good aeration is an important feature in maintaining high quality grain. In order to achieve good aeration, aeration time needs to be determined. It would take a lot of effort to develop and test the actual aeration to find an aeration time, because it is affected by many parameters such as temperature and moisture content. A computer simulation of aeration could determine the aeration time.

The purpose of this study was to develop a personal computer calculation model which simulates wheat aeration of a fixed bed bin. An aeration simulation program was developed to find the appropriate time for aeration of hard red winter wheat. To simulate a fixed bed aeration, a calculation model was developed based upon Parry's general model (eq. 6). Particular conditions of a fixed bed aeration were applied to the calculation model (objective 1). After the model was developed, a computer program (objective 2) was implemented to simulate hard red winter

wheat aeration. From information obtained in this study, the evaluation of the simulation program (objective 3) can be summarized as follows:

- At every simulation, temperature prediction error increased until the simulation reached the middle of aeration time. After that the prediction error decreased to a minimum at the final time of aeration.

- prediction of grain moisture content does not show a correlation with the measured moisture content, but at low airflow rates (less than $4.0 \text{ l/(sm}^3\text{)}$, Figure 24), average absolute error is within 1%.

- Higher volumetric airflow rate has an effect on increasing the average absolute error of grain temperature and moisture content.

All of the above findings are the result of the initial assumptions of the calculation model which have been made to reduce the complexity of the model. In the actual testing, some initial assumptions were found not to be precisely correct; for instance, one assumption made earlier in the study is the slow heat and mass transfer between grain and medium fluid which does not occur at the higher airflow rate.

The calculation program, because of the above results, is not a good predictor (without further modification) to predict grain temperatures at the middle of the aeration time at high airflow rate (greater than $8.04 \text{ l/(sm}^3\text{)})$. However, the prediction at the final stage is acceptable to predict the aeration time. Therefore, fixed bed aeration time of hard red winter wheat can be predicted by this computer simulation program.

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APPENDIXES

APPENDIX A

RESULTS OF EXPERIMENTAL DATA

This following tables show the experimental grain temperature results (Epperly, 1989) of wheat aeration:

TABLE IX

EXPERIMENTAL DATA AT $Q = 0.67, 1.34$ AND $2.68 \text{ l}/(\text{sm}^3)$

Q : unit airflow rate [$\text{Litre}/(\text{sm}^3)$]

Temperature : $^{\circ}\text{C}$

X/L	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
<hr/>											
$Q=0.67$											
25h	14.4	22.8	31.0	35.0	36.0	36.2	36.6	36.9	37.2	37.2	37.2
50h	14.4	16.8	22.0	29.0	33.8	36.0	36.5	36.6	36.8	36.8	36.8
150h	14.4	14.4	14.5	15.1	17.0	19.2	22.0	25.0	27.6	30.0	30.0
$Q=1.34$											
10h	14.4	26.9	34.9	37.0	37.4	37.8	38.3	38.3	38.3	38.3	38.3
25h	14.4	15.6	22.3	29.3	34.1	36.9	38.0	38.3	38.3	38.3	38.3
55h	14.4	14.4	14.8	17.0	20.2	24.3	28.1	31.7	34.4	36.2	36.7
100h	14.4	14.4	14.8	15.5	16.2	16.8	18.2	20.0	21.2	24.7	26.1
$Q=2.68$											
10h	14.4	17.7	28.9	34.9	36.8	37.2	37.2	37.2	37.2	37.2	37.2
20h	14.4	14.6	18.4	24.6	30.0	34.1	36.6	37.2	37.2	37.2	37.2
40h	14.4	14.4	14.9	15.9	18.4	21.4	24.9	28.1	30.7	33.2	34.3
70h	14.4	14.4	14.4	15.4	15.9	16.8	17.6	18.6	20.5	22.1	24.1

TABLE X

EXPERIMENTAL DATA AT $Q = 5.36, 8.04$ AND $10.7 \text{ l/(sm}^3\text{)}$ Q : unit airflow rate [$\text{Litre/(sm}^3\text{)}$]Temperature : $^{\circ}\text{C}$

X/L	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
$Q=5.36$											
2h	18.3	28.7	33.4	35.7	35.8	35.8	36.1	36.7	36.7	36.7	36.7
6h	18.3	19.7	22.9	27.6	30.8	33.2	35.0	36.2	36.4	36.7	36.7
12h	18.3	18.9	18.8	20.3	22.0	23.4	26.8	29.7	31.8	33.8	34.3
24h	18.3	18.3	18.7	19.0	19.0	19.0	19.7	20.6	21.6	23.3	28.0
$Q=8.04$											
2h	17.8	27.6	32.7	35.7	37.9	38.3	38.3	38.3	38.3	38.3	38.3
5h	17.8	21.0	23.5	25.5	29.1	31.8	34.1	36.2	37.6	38.3	38.3
12h	17.8	18.0	19.5	19.3	20.0	21.2	22.6	24.6	26.8	28.9	30.1
20h	17.8	18.0	18.3	18.7	18.8	19.0	19.2	19.7	20.6	21.5	25.3
$Q=10.72$											
1h	18.9	30.0	33.8	35.0	35.0	35.0	35.0	35.0	35.0	35.0	35.0
2h	18.9	25.0	29.1	31.6	33.5	34.5	35.0	35.0	35.0	35.0	35.0
4h	18.9	19.8	23.0	25.2	27.6	29.8	32.0	33.4	34.2	34.8	35.0
8h	18.9	18.9	19.8	20.2	21.0	22.2	23.8	25.8	27.6	29.4	31.6
14h	18.9	18.9	18.9	18.9	18.9	18.9	19.3	19.8	20.6	21.8	23.4

APPENDIX B

SIMULATION RESULTS

The following data show the simulation printout of wheat aeration $Q = 0.67, 1.34, 2.68, \text{ and } 10.72 \text{ l/(sm}^3\text{)}$:

```

Desired Time = 275.08 hrs
AIR VELOCITY = 0.36 ft/min
AIR VOLUME   = 0.05 CFM/bush or 0.67 l/s/cu.m
No. Node = 10 : Length = 9.00 [ft]
dx = 0.90 [ft]
dt = 0.050 [min]      BM = 0.01
Temp 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Temp 14.4 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2
Mdb 13.9 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
5hr T = 34.8 37.1 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2
5hr M = 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
10hr T = 31.8 36.6 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2
10hr M = 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
15hr T = 28.9 35.8 37.0 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2
15hr M = 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
20hr T = 26.2 34.6 36.8 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2
20hr M = 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
25hr T = 23.6 33.2 36.4 37.1 37.2 37.2 37.2 37.2 37.2 37.2 37.2
25hr M = 14.1 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
30hr T = 21.3 31.5 35.7 37.0 37.2 37.2 37.2 37.2 37.2 37.2 37.2
30hr M = 14.1 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
35hr T = 19.1 29.7 34.9 36.7 37.1 37.2 37.2 37.2 37.2 37.2 37.2
35hr M = 14.0 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
40hr T = 17.3 27.8 33.9 36.4 37.0 37.2 37.2 37.2 37.2 37.2 37.2
40hr M = 14.0 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
45hr T = 15.8 25.8 32.7 35.9 36.9 37.2 37.2 37.2 37.2 37.2 37.2
45hr M = 13.9 14.2 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
50hr T = 14.7 23.9 31.2 35.3 36.7 37.1 37.2 37.2 37.2 37.2 37.2
50hr M = 13.9 14.1 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
55hr T = 14.4 22.1 29.7 34.6 36.4 37.0 37.2 37.2 37.2 37.2 37.2
55hr M = 13.9 14.1 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
60hr T = 14.4 20.5 28.0 33.7 36.1 36.9 37.2 37.2 37.2 37.2 37.2
60hr M = 13.9 14.1 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
65hr T = 14.4 19.1 26.2 32.6 35.6 36.8 37.1 37.2 37.2 37.2 37.2
65hr M = 13.9 14.0 14.2 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3
70hr T = 14.4 17.9 24.4 31.4 35.0 36.6 37.0 37.2 37.2 37.2 37.2
70hr M = 13.9 14.0 14.1 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3
75hr T = 14.4 17.0 22.7 30.1 34.2 36.3 36.9 37.2 37.2 37.2 37.2
75hr M = 13.9 14.0 14.1 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3
80hr T = 14.4 16.2 21.0 28.7 33.3 35.9 36.8 37.1 37.2 37.2 37.2
80hr M = 13.9 14.0 14.1 14.2 14.2 14.3 14.3 14.3 14.3 14.3 14.3
85hr T = 14.4 15.6 19.4 27.2 32.3 35.4 36.6 37.1 37.2 37.2 37.2
85hr M = 13.9 13.9 14.0 14.2 14.2 14.3 14.3 14.3 14.3 14.3 14.3

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90hr T = 14.4 15.2 18.0 25.7 31.2 34.8 36.4 37.0 37.2 37.2
 90hr M = 13.9 13.9 14.0 14.2 14.2 14.3 14.3 14.3 14.3 14.3
 95hr T = 14.4 14.9 16.7 24.1 29.9 34.1 36.0 36.9 37.1 37.2
 95hr M = 13.9 13.9 14.0 14.1 14.2 14.3 14.3 14.3 14.3 14.3
 100hr T = 14.4 14.7 15.5 22.6 28.6 33.3 35.6 36.7 37.1 37.2
 100hr M = 13.9 13.9 13.9 14.1 14.2 14.2 14.3 14.3 14.3 14.3
 105hr T = 14.4 14.7 14.7 21.2 27.1 32.4 35.2 36.5 37.0 37.2
 105hr M = 13.9 13.9 13.9 14.1 14.2 14.2 14.3 14.3 14.3 14.3
 110hr T = 14.4 14.6 14.6 19.9 25.6 31.4 34.6 36.3 36.9 37.1
 110hr M = 13.9 13.9 13.9 14.0 14.2 14.2 14.3 14.3 14.3 14.3
 115hr T = 14.4 14.6 14.6 18.8 24.1 30.3 33.9 35.9 36.8 37.1
 115hr M = 13.9 13.9 13.9 14.0 14.1 14.2 14.3 14.3 14.3 14.3
 120hr T = 14.4 14.6 14.6 17.9 22.6 29.1 33.1 35.5 36.6 37.0
 120hr M = 13.9 13.9 13.9 14.0 14.1 14.2 14.2 14.3 14.3 14.3
 125hr T = 14.4 14.6 14.6 17.1 21.1 27.8 32.2 35.1 36.4 36.9
 125hr M = 13.9 13.9 13.9 14.0 14.1 14.2 14.2 14.3 14.3 14.3
 130hr T = 14.4 14.6 14.6 16.5 19.8 26.5 31.2 34.5 36.1 36.8
 130hr M = 13.9 13.9 13.9 14.0 14.0 14.2 14.2 14.3 14.3 14.3
 135hr T = 14.4 14.6 14.6 16.0 18.5 25.2 30.1 33.9 35.8 36.7
 135hr M = 13.9 13.9 13.9 14.0 14.0 14.1 14.2 14.3 14.3 14.3
 140hr T = 14.4 14.5 14.5 15.6 17.4 23.9 28.9 33.2 35.4 36.5
 140hr M = 13.9 13.9 13.9 13.9 14.0 14.1 14.2 14.2 14.3 14.3
 145hr T = 14.4 14.5 14.5 15.4 16.4 22.6 27.7 32.3 34.9 36.3
 145hr M = 13.9 13.9 13.9 13.9 14.0 14.1 14.2 14.2 14.3 14.3
 150hr T = 14.4 14.5 14.5 15.3 15.7 21.4 26.4 31.4 34.3 36.0
 150hr M = 13.9 13.9 13.9 13.9 13.9 14.1 14.2 14.2 14.3 14.3
 155hr T = 14.4 14.5 14.5 15.2 15.2 20.3 25.0 30.4 33.7 35.7
 155hr M = 13.9 13.9 13.9 13.9 13.9 14.1 14.1 14.2 14.3 14.3
 160hr T = 14.4 14.5 14.5 15.1 15.1 19.3 23.7 29.4 32.9 35.3
 160hr M = 13.9 13.9 13.9 13.9 13.9 14.0 14.1 14.2 14.2 14.3
 165hr T = 14.4 14.5 14.5 15.0 15.0 18.5 22.4 28.3 32.1 34.9
 165hr M = 13.9 13.9 13.9 13.9 13.9 14.0 14.1 14.2 14.2 14.3
 170hr T = 14.4 14.5 14.5 15.0 15.0 17.8 21.1 27.1 31.2 34.4
 170hr M = 13.9 13.9 13.9 13.9 13.9 14.0 14.1 14.2 14.2 14.3
 175hr T = 14.4 14.5 14.5 14.9 14.9 17.2 19.9 26.0 30.2 33.8
 175hr M = 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.2 14.2 14.3
 180hr T = 14.4 14.5 14.5 14.9 14.9 16.7 18.8 24.8 29.1 33.1
 180hr M = 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1 14.2 14.2
 185hr T = 14.4 14.5 14.5 14.9 14.9 16.4 17.8 23.6 28.0 32.4
 185hr M = 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1 14.2 14.2
 190hr T = 14.4 14.5 14.5 14.8 14.8 16.1 16.9 22.5 26.8 31.7
 190hr M = 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1 14.2 14.2
 195hr T = 14.4 14.5 14.5 14.8 14.8 15.9 16.1 21.4 25.6 30.8
 195hr M = 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1 14.1 14.2
 200hr T = 14.4 14.5 14.5 14.8 14.8 15.8 15.8 20.4 24.3 30.0
 200hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.1 14.1 14.2
 205hr T = 14.4 14.5 14.5 14.7 14.7 15.7 15.7 19.6 23.1 29.1
 205hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.1 14.2
 210hr T = 14.4 14.5 14.5 14.7 14.7 15.6 15.6 18.9 21.8 28.1
 210hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.1 14.2
 215hr T = 14.4 14.5 14.5 14.7 14.7 15.5 15.5 18.3 20.6 27.2
 215hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.1 14.2
 220hr T = 14.4 14.5 14.5 14.7 14.7 15.5 15.5 17.8 19.5 26.4
 220hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.2
 225hr T = 14.4 14.5 14.5 14.6 14.6 15.4 15.4 17.4 18.4 25.5
 225hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
 230hr T = 14.4 14.5 14.5 14.6 14.6 15.3 15.3 17.2 17.4 24.7
 230hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
 235hr T = 14.4 14.5 14.5 14.6 14.6 15.2 15.2 17.0 17.0 23.9
 235hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
 240hr T = 14.4 14.5 14.5 14.6 14.6 15.2 15.2 16.8 16.8 23.1
 240hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
 245hr T = 14.4 14.5 14.5 14.6 14.6 15.1 15.1 16.7 16.7 22.5

```

245hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
250hr T = 14.4 14.5 14.5 14.6 14.6 15.1 15.1 16.5 16.5 21.8
250hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
255hr T = 14.4 14.5 14.5 14.6 14.6 15.0 15.0 16.4 16.4 21.3
255hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
260hr T = 14.4 14.5 14.5 14.5 14.5 15.0 15.0 16.2 16.2 20.8
260hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
265hr T = 14.4 14.5 14.5 14.5 14.5 14.9 14.9 16.1 16.1 20.3
265hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
270hr T = 14.4 14.5 14.5 14.5 14.5 14.9 14.9 16.0 16.0 19.9
270hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.0
275hr T = 14.4 14.5 14.5 14.5 14.5 14.9 14.9 15.9 15.9 19.5
275hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.0

```

Desired Time = 135.08 hrs

AIR VELOCITY = 0.72 ft/min

AIR VOLUME = 0.10 CFM/bush or 1.34 l/s/cu.m

No. Node = 10 : Length = 9.00 [ft]

dx = 0.90 [ft]

dt = 0.050 [min] BM = 0.01

Temp	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.0
Temp	14.4	38.3	38.3	38.3	38.3	38.3	38.3	38.3	38.3	38.3	38.3
Mdb	13.9	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
5hr T	32.6	37.7	38.3	38.3	38.3	38.3	38.3	38.3	38.3	38.3	38.3
5hr M	14.2	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
10hr T	26.8	35.6	37.9	38.3	38.3	38.3	38.3	38.3	38.3	38.3	38.3
10hr M	14.2	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
15hr T	21.6	32.3	36.8	38.0	38.3	38.3	38.3	38.3	38.3	38.3	38.3
15hr M	14.1	14.2	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
20hr T	17.4	28.3	34.8	37.4	38.1	38.3	38.3	38.3	38.3	38.3	38.3
20hr M	14.0	14.2	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
25hr T	14.7	24.1	32.0	36.3	37.8	38.2	38.3	38.3	38.3	38.3	38.3
25hr M	13.9	14.1	14.2	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
30hr T	14.4	20.4	28.5	34.5	37.1	38.0	38.3	38.3	38.3	38.3	38.3
30hr M	13.9	14.1	14.2	14.3	14.3	14.3	14.3	14.3	14.3	14.3	14.3
35hr T	14.4	17.6	24.7	32.0	35.9	37.6	38.1	38.3	38.3	38.3	38.3
35hr M	13.9	14.0	14.1	14.2	14.3	14.3	14.3	14.3	14.3	14.3	14.3
40hr T	14.4	15.7	21.0	29.0	34.1	36.8	37.9	38.2	38.3	38.3	38.3
40hr M	13.9	13.9	14.1	14.2	14.2	14.3	14.3	14.3	14.3	14.3	14.3
45hr T	14.4	14.6	17.8	25.7	31.8	35.7	37.4	38.0	38.3	38.3	38.3
45hr M	13.9	13.9	14.0	14.1	14.2	14.3	14.3	14.3	14.3	14.3	14.3
50hr T	14.4	14.4	15.3	22.4	28.9	34.0	36.6	37.7	38.2	38.3	38.3
50hr M	13.9	13.9	13.9	14.1	14.2	14.2	14.3	14.3	14.3	14.3	14.3
55hr T	14.4	14.4	14.4	19.4	25.7	31.8	35.4	37.2	38.0	38.2	38.2
55hr M	13.9	13.9	13.9	14.0	14.1	14.2	14.3	14.3	14.3	14.3	14.3
60hr T	14.4	14.4	14.4	17.2	22.5	29.2	33.7	36.4	37.6	38.1	38.1
60hr M	13.9	13.9	13.9	14.0	14.1	14.2	14.2	14.3	14.3	14.3	14.3
65hr T	14.4	14.4	14.4	15.8	19.5	26.4	31.6	35.2	37.0	37.9	37.9
65hr M	13.9	13.9	13.9	13.9	14.0	14.2	14.2	14.3	14.3	14.3	14.3
70hr T	14.4	14.4	14.4	14.9	17.0	23.5	29.1	33.7	36.2	37.5	37.5
70hr M	13.9	13.9	13.9	13.9	14.0	14.1	14.2	14.2	14.3	14.3	14.3
75hr T	14.4	14.4	14.4	14.6	15.0	20.7	26.3	31.7	35.0	36.9	36.9
75hr M	13.9	13.9	13.9	13.9	13.9	14.1	14.2	14.2	14.3	14.3	14.3
80hr T	14.4	14.4	14.4	14.6	14.6	18.4	23.4	29.4	33.4	36.1	36.1
80hr M	13.9	13.9	13.9	13.9	13.9	14.0	14.1	14.2	14.2	14.3	14.3
85hr T	14.4	14.4	14.4	14.5	14.5	16.7	20.6	26.8	31.5	35.0	35.0
85hr M	13.9	13.9	13.9	13.9	13.9	14.0	14.1	14.2	14.2	14.3	14.3
90hr T	14.4	14.4	14.4	14.5	14.5	15.6	18.1	24.2	29.1	33.6	33.6
90hr M	13.9	13.9	13.9	13.9	13.9	13.9	14.0	14.1	14.2	14.2	14.2
95hr T	14.4	14.4	14.4	14.5	14.5	15.1	16.1	21.6	26.5	31.8	31.8
95hr M	13.9	13.9	13.9	13.9	13.9	13.9	14.0	14.1	14.2	14.2	14.2
100hr T	14.4	14.4	14.4	14.5	14.5	14.9	14.9	19.3	23.8	29.9	29.9

```

100hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.1 14.2
105hr T = 14.4 14.4 14.4 14.5 14.5 14.8 14.8 17.6 21.0 27.8
105hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.1 14.2
110hr T = 14.4 14.4 14.4 14.5 14.5 14.7 14.7 16.5 18.5 25.8
110hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
115hr T = 14.4 14.4 14.4 14.5 14.5 14.7 14.7 15.9 16.2 24.0
115hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.1
120hr T = 14.4 14.4 14.4 14.5 14.5 14.6 14.6 15.7 15.7 22.3
120hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.1
125hr T = 14.4 14.4 14.4 14.5 14.5 14.6 14.6 15.5 15.5 20.9
125hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.1
130hr T = 14.4 14.4 14.4 14.5 14.5 14.6 14.6 15.3 15.3 19.7
130hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0
135hr T = 14.4 14.4 14.4 14.5 14.5 14.6 14.6 15.2 15.2 18.8
135hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0

```

Desired Time = 88.08 hrs

AIR VELOCITY = 1.45 ft/min

AIR VOLUME = 0.20 CFM/bush or 2.68 l/s/cu.m

No. Node = 10 : Length = 9.00 [ft]

dx = 0.90 [ft]

dt = 0.050 [min] BM = 0.01

```

Temp 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
Temp 14.4 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2
Mdb 13.9 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
5hr T = 26.2 34.6 36.8 37.2 37.2 37.2 37.2 37.2 37.2 37.2 37.2
5hr M = 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
10hr T = 18.8 27.8 33.9 36.4 37.0 37.2 37.2 37.2 37.2 37.2 37.2
10hr M = 14.0 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
15hr T = 16.3 21.3 28.2 33.6 36.0 36.9 37.2 37.2 37.2 37.2 37.2
15hr M = 14.0 14.1 14.2 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
20hr T = 15.4 17.1 22.0 28.7 33.3 35.8 36.8 37.1 37.2 37.2 37.2
20hr M = 13.9 14.0 14.1 14.2 14.2 14.3 14.3 14.3 14.3 14.3 14.3
25hr T = 15.1 15.1 18.5 23.4 28.7 33.2 35.6 36.7 37.1 37.2 37.2
25hr M = 13.9 13.9 14.0 14.1 14.2 14.2 14.3 14.3 14.3 14.3 14.3
30hr T = 15.0 15.0 16.9 19.4 23.5 29.1 33.0 35.5 36.5 37.0 37.0
30hr M = 13.9 13.9 14.0 14.0 14.1 14.2 14.2 14.3 14.3 14.3 14.3
35hr T = 14.9 14.9 16.2 17.1 19.9 24.5 29.0 33.0 35.3 36.5 36.5
35hr M = 13.9 13.9 14.0 14.0 14.0 14.1 14.2 14.2 14.3 14.3 14.3
40hr T = 14.9 14.9 15.9 15.9 18.0 20.7 24.4 29.3 32.8 35.2 35.2
40hr M = 13.9 13.9 14.0 14.0 14.0 14.1 14.1 14.2 14.2 14.3 14.3
45hr T = 14.8 14.8 15.7 15.7 17.1 18.5 20.7 25.1 29.2 33.0 33.0
45hr M = 13.9 13.9 13.9 13.9 14.0 14.0 14.1 14.1 14.2 14.2 14.2
50hr T = 14.8 14.8 15.6 15.6 16.6 17.2 18.7 21.6 24.8 29.9 29.9
50hr M = 13.9 13.9 13.9 13.9 14.0 14.0 14.0 14.1 14.1 14.2 14.2
55hr T = 14.7 14.7 15.4 15.4 16.3 16.4 17.7 19.5 21.0 26.7 26.7
55hr M = 13.9 13.9 13.9 13.9 14.0 14.0 14.0 14.0 14.1 14.2 14.2
60hr T = 14.7 14.7 15.3 15.3 16.1 16.1 17.1 18.4 18.6 24.0 24.0
60hr M = 13.9 13.9 13.9 13.9 14.0 14.0 14.0 14.0 14.0 14.1 14.1
65hr T = 14.6 14.6 15.2 15.2 16.0 16.0 16.6 17.8 17.8 21.8 21.8
65hr M = 13.9 13.9 13.9 13.9 14.0 14.0 14.0 14.0 14.0 14.1 14.1
70hr T = 14.6 14.6 15.1 15.1 15.9 15.9 16.3 17.3 17.3 20.2 20.2
70hr M = 13.9 13.9 13.9 13.9 14.0 14.0 14.0 14.0 14.0 14.1 14.1
75hr T = 14.6 14.6 15.1 15.1 15.8 15.8 16.1 16.9 16.9 19.1 19.1
75hr M = 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.0 14.0 14.0
80hr T = 14.6 14.6 15.0 15.0 15.7 15.7 15.9 16.6 16.6 18.2 18.2
80hr M = 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.0 14.0 14.0
85hr T = 14.6 14.6 15.0 15.0 15.6 15.6 15.8 16.3 16.3 17.6 17.6
85hr M = 13.9 13.9 13.9 13.9 13.9 13.9 13.9 14.0 14.0 14.0 14.0

```

Desired Time = 21.02 hrs
 AIR VELOCITY = 5.79 ft/min
 AIR VOLUME = 0.80 CFM/bush or 10.72 l/s/cu.m
 No. Node = 10 : Length = 9.00 [ft]
 dx = 0.90 [ft]
 dt = 0.050 [min] BM = 0.01
 Temp 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0
 Temp 18.9 35.0 35.0 35.0 35.0 35.0 35.0 35.0 35.0 35.0 35.0
 Mdb 11.5 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
 1hr T = 28.7 33.8 34.8 35.0 35.0 35.0 35.0 35.0 35.0 35.0
 1hr M = 13.5 14.1 14.3 14.3 14.3 14.3 14.3 14.3 14.3 14.3
 2hr T = 23.3 30.4 33.7 34.7 35.0 35.0 35.0 35.0 35.0 35.0
 2hr M = 12.5 13.7 14.1 14.3 14.3 14.3 14.3 14.3 14.3 14.3
 3hr T = 20.2 26.1 31.2 33.8 34.7 34.9 35.0 35.0 35.0 35.0
 3hr M = 11.8 13.0 13.8 14.1 14.3 14.3 14.3 14.3 14.3 14.3
 4hr T = 18.9 22.3 27.5 31.8 33.9 34.7 34.9 35.0 35.0 35.0
 4hr M = 11.5 12.3 13.3 13.9 14.2 14.3 14.3 14.3 14.3 14.3
 5hr T = 18.9 19.9 23.5 28.8 32.2 34.0 34.7 34.9 35.0 35.0
 5hr M = 11.5 11.7 12.5 13.5 13.9 14.2 14.3 14.3 14.3 14.3
 6hr T = 18.9 18.9 20.8 25.4 29.5 32.6 34.1 34.7 34.9 35.0
 6hr M = 11.5 11.5 12.0 12.9 13.6 14.0 14.2 14.3 14.3 14.3
 7hr T = 18.9 18.9 19.5 22.4 26.3 30.4 32.9 34.2 34.7 34.9
 7hr M = 11.5 11.5 11.6 12.3 13.1 13.7 14.0 14.2 14.3 14.3
 8hr T = 18.9 18.9 18.9 20.3 23.1 27.5 30.9 33.2 34.2 34.7
 8hr M = 11.5 11.5 11.5 11.8 12.5 13.3 13.8 14.1 14.2 14.3
 9hr T = 18.9 18.9 18.9 19.2 20.8 24.6 28.2 31.5 33.3 34.3
 9hr M = 11.5 11.5 11.5 11.6 12.0 12.7 13.4 13.8 14.1 14.2
 10hr T = 18.9 18.9 18.9 18.9 19.6 22.1 25.2 29.1 31.8 33.6
 10hr M = 11.5 11.5 11.5 11.5 11.7 12.2 12.9 13.5 13.9 14.1
 11hr T = 18.9 18.9 18.9 18.9 19.0 20.4 22.4 26.4 29.6 32.3
 11hr M = 11.5 11.5 11.5 11.5 11.5 11.9 12.3 13.1 13.6 14.0
 12hr T = 18.9 18.9 18.9 18.9 18.9 19.5 20.5 23.8 26.9 30.5
 12hr M = 11.5 11.5 11.5 11.5 11.5 11.6 11.9 12.6 13.2 13.7
 13hr T = 18.9 18.9 18.9 18.9 18.9 19.1 19.4 21.7 24.0 28.4
 13hr M = 11.5 11.5 11.5 11.5 11.5 11.5 11.6 12.2 12.6 13.4
 14hr T = 18.9 18.9 18.9 18.9 18.9 19.0 19.0 20.4 21.5 26.3
 14hr M = 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.9 12.1 13.1
 15hr T = 18.9 18.9 18.9 18.9 18.9 19.0 19.0 19.8 19.8 24.4
 15hr M = 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.7 11.7 12.7
 16hr T = 18.9 18.9 18.9 18.9 18.9 18.9 18.9 19.5 19.5 22.9
 16hr M = 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.6 11.6 12.4
 17hr T = 18.9 18.9 18.9 18.9 18.9 18.9 18.9 19.4 19.4 21.8
 17hr M = 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.6 11.6 12.2
 18hr T = 18.9 18.9 18.9 18.9 18.9 18.9 18.9 19.2 19.2 21.0
 18hr M = 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.6 11.6 12.0
 19hr T = 18.9 18.9 18.9 18.9 18.9 18.9 18.9 19.1 19.1 20.5
 19hr M = 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.9
 20hr T = 18.9 18.9 18.9 18.9 18.9 18.9 18.9 19.1 19.1 20.0
 20hr M = 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.8
 21hr T = 18.9 18.9 18.9 18.9 18.9 18.9 18.9 19.0 19.0 19.7
 21hr M = 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.5 11.7

APPENDIX C

PROGRAM CODE

The calculation program was code by C language.
Program editor and compiler are Turbo C 2.0 software program
from Borland company.

```

/*****
/*          AERATION RESEARCH Project
/*          by using CRANK-NICOLSON implicit method
/*          Sukit NITINAI   May 9, 97
/*
/*          Hard red winter wheat  Mi = 0.129 wb  (14.3% db)
*****/

#include<stdio.h>
#include<math.h>
#define node      10          /* No. of node in x-axis */
#define EPSILON  1e-3          /* Iteration criterion per unit */
#define P_ATM    14.696        /* Atmospheric pressure [psia] */

void calc_T_H();
double EMC(), ERH(), dM(), M();
double hfg(), Pvs(), RH(), H();

double Ti, Hi, DX, H0, HN, BM, R, CMT, CMH;
double Told[node+5], Tnew[node+5];
double Hold[node+5], Hnew[node+5];
double Mold[node+5], Mnew[node+5];
double VR, ro_a, ro_p, v_a, ca, cv, cw, cp, Tai, Tgi, dt;
double EMCi, Hai, Hgi;

main()
{
    long int istep, nstep;
    int i, j, icount, iprn, status, N;
    double sumerr, L, endtime;
    double Tnew_p[node+5], Hnew_p[node+5];
    double CFM_BU;

    clrscr();

    /*****   initialized data and constant   *****/

    CFM_BU = 0.8 ;    /* Volume of air [cu.ft/bush] */
    VR      = 0.448 ; /* void ratio */
    ro_a    = 0.077775; /* air density lb/cu ft (50F) */

```

```

ro_p = 49.78;      /* product density lb/cu ft */
v_a  = CFM_BU*7.23182; /* air velocity ft/min */
ca   = 0.2397 ;    /* specific heat of air Btu/lb-F */
cp   = 0.42 ;      /* specific heat of product Btu/lb-F */
cv   = 0.4472;     /* specific heat of vapor Btu/lb-F */
cw   = 1. ;        /* specific heat of water in grain Btu/lb-F*/

L = 9.0 ;          /* Length of BED, feet */
dt = .05 ;         /* time step, min */
iprn = 1200;       /* print every 1200 step */
endtime = 1261.;   /* total time, min */
Tai = 66. ;        /* T air enter, deg F */
Hai = 0.005;       /* entering Humidity ratio, lb/lb */
Tgi = 95. ;        /* Ti grain, deg F */
EMCi = 0.14286;    /* decimal unit mdb */

Hgi = H(ERH(EMCi,Tgi),Tgi); /* Hin grain, lb/lb */

DX = L/node;
BM = 0.25*dt/DX;    /* Const [min/ft] */
nstep = (long int) (endtime/dt) + 1;

printf("\n Desired Time = %5.2f hrs", endtime/60.);
printf("\n AIR VELOCITY = %5.2f ft/min",v_a);
printf("\n AIR VOLUME = %5.2f CFM/bush",CFM_BU);
printf(" or %5.2f l/s/cu.m" ,CFM_BU*13.4);
printf("\n No. Node = %d : Length = %6.2f [ft]",node,L);

printf("\n dx = %6.2f [ft]",DX);
printf("\n dt = %6.3f [min] BM =%5.2f",dt,BM);

Told[0] = Tnew[0] = Tai;
Hold[0] = Hnew[0] = Hai;

N = node + 2;      /* add ficticius nodes */
for(i=1;i<=N;i++) {
    Told[i] = Tgi;
    Hold[i] = Hgi;
}
printf(" \n Temp");
for(i=0;i<=node;i++) printf("%5.1f",i*0.1);

printf(" \n Temp");
for(i=0;i<=node;i++) printf("%5.1f", (Told[i]-32.)/1.8);

printf(" \n Mdb ");
for(i=0;i<=node;i++) printf("%5.1f",100*EMC(Hold[i],Told[i]));

/***** STARTING POINT TIME = 0.0 *****/

for(istep=1;istep<=nstep;istep++)
{
    sumerr = 5.;    /* Initial for enter loop */
    icount = 0;
    CMT = 0.0;
    CMH = 1.0;

    Tnew[0] = Told[0] ;
    Hnew[0] = Hold[0] ;

    /* GUESS TEMP. */
    for(i=1;i<=N;i++) {

```

```

        Tnew[i] = Told[i];
        Hnew[i] = Hold[i];
        Tnew_p[i] = 0.;
        Hnew_p[i] = 0.;
    }
    /* ITERATION LOOP until unchanged T and H */
while( sumerr > EPSILON )
{
    sumerr=0.;
    if (icount > 10 ) break;

    for(i=1;i<N;i++)
    {
        if(i == N) (Told[N]=Tnew[N]=Told[N-1]);
        calc_T_H(i);

        sumerr += fabs((Tnew[i]-Tnew_p[i])/Tnew[i]);
        sumerr += fabs((Hnew[i]-Hnew_p[i])/Hnew[i]);

        Hnew_p[i] = Hnew[i];
        Tnew_p[i] = Tnew[i];

    } /* end sweep i = 1 to N */
    ++icount;
    /* end if icount */
} /* end while A */
sumerr = 2.;
icount = 0;

CMT = 1.0;
CMH = 0.0;
while( sumerr > EPSILON )
{
    sumerr=0.;
    if (icount > 10 ) break;

    for(i=1;i<N;i++)
    {
        if(i == N) (Told[N]=Tnew[N]=Told[N-1]);
        calc_T_H(i);

        sumerr += fabs((Tnew[i]-Tnew_p[i])/Tnew[i]);
        sumerr += fabs((Hnew[i]-Hnew_p[i])/Hnew[i]);

        Hnew_p[i] = Hnew[i];
        Tnew_p[i] = Tnew[i];

    } /* end sweep i = 1 to N */
    ++icount;
    /* end if icount */
} /* end while */

for(i=1;i<=N;i++) Hold[i] = Hnew[i];
for(i=1;i<=N;i++) Told[i] = Tnew[i];
for(i=1;i<=N;i++) Mold[i] = Mnew[i];

/***** PRINT RESULTS *****/

if(istep%iprn==0 )
{
    printf("\n%4.0fhr T =",dt*istep/60);

```



```

        for(i=1;i<=node;i++)
            printf("%5.1f", (Tnew[i]-32)/1.8);

        printf("\n%4.0fhr M =",dt*istep/60.);
        for(i=1;i<=node;i++)
            printf("%5.1f",100.*M(i));

    )
    /* goto next time step */
}
/* end istep */

/***** FINISH at to endtime *****/
)
/***** END OF THE PROGRAM *****/

void calc_T_H(int i)
{
    double del_M,TF,H,DT,DH;
    double A,B,C,D,E,F,G,M1,M2;

    M1 = EMC(Hold[i],Told[i]);
    M2 = dM(i) + M1;
    if(M1<0.04) M1 = 0.04;
    if(M1>0.25) M1 = 0.25;
    if(M2<0.04) M2 = 0.04;
    if(M2>0.25) M2 = 0.25;
    G = 6.;
    TF = Told[i];
    H = Hold[i];

    del_M = M1 - M2;

    A = -1.*v_a;
    B = 2.*ro_p/(VR*ro_a);

    D = VR*ro_a*G*(ca+cv*H)+ro_p*(cp+cw*M1);
    E = 2.*ro_p* ((cw-cv)*(TF-32.) -hfg(TF));
    F = -VR*ro_a*G*v_a*(ca+cv*H);

    DT = BM*F/D*(Told[i+1]-Told[i-1]+Tnew[i+1]-Tnew[i-1])+E/D*del_M*CMT;

    DH = BM*A*(Hold[i+1]-Hold[i-1]+Hnew[i+1]-Hnew[i-1]) + B*del_M*CMH ;

    Tnew[i] = Told[i]+DT;
    Hnew[i] = Hold[i]+DH;
    Mnew[i] = M2;

    if(Tnew[i] > Told[i]) Tnew[i]=Told[i];
    if(Tnew[i] < Tnew[i-1]) Tnew[i]=0.5*(Tnew[i-1]+TF);
    if(Hnew[i] > 0.03) Hnew[i]=0.03;
    if(Hnew[i] < 0.0) Hnew[i]=0.0005;
}

double hfg(double TF)
{
    /*****
    /* This fuction calc. hfg [BTU/lb]
    /* of vapor from temp. 32 F to 120 F
    *****/
    double BTU;

```



```

        BTU = 1093.3136-0.56761364*TF;
        return(BTU);
    }

double EMC(double H, double T)
{
    /******
    /* This sub. return EMC, decimal unit db          */
    /* H      : humidity ratio, lb/lb dry air          */
    /* T      : Temp, deg F (dry bulb)                 */
    /* TC     : Temp, deg C (dry bulb)                 */
    /* mdb    : EMC % dry basis                        */
    /* Rh     : Relative Humidity [decimal unit]       */
    /* Use only for red wheat                          */
    /******
    double mdb,Rh,TC;

    Rh=RH(H,T);
    TC= (T-32.)/1.8;
    mdb =pow( log(1.-Rh)/(-2.3008e-5* (TC+55.815)), (1./2.2857));
    return (mdb*.01);
}

double H(double RH,double T)
{
    /******
    /* This sub. calc. Humidity Ratio [lb/lb]          */
    /* from Relative Humidity and Temp [deg F]        */
    /* Patm   : atmospheric pressure [psia]           */
    /* Ps     : sat. vapor pressure [psia]            */
    /******
    double H,Patm,Pv;

    Patm = P_ATM;
    Pv   = Pvs(T)*RH;
    H    = (0.62198)*Pv/(Patm-Pv);
    return(H);
}

double Pvs(double T)
{
    /******
    /* This sub. calc. Sat vapor pressure [psia]      */
    /* from Temp [deg F]                             */
    /* 32 F < T < 180 F                             */
    /* TRK    : Temp rankine [R]                     */
    /******
    double TRK;

    TRK = T + 459.67;
    return (exp(-10440.4/TRK -11.2946669 -0.02700133*TRK \
        +1.289706e-5*TRK*TRK -2.478068e-9 *TRK*TRK*TRK \
        +6.5459673*log(TRK)));
}

double RH(double H,double T)
{
    /******
    /* This sub. calc. Relative Humid.[decimal]      */
    /* from Humid. ratio and Temp, deg F             */
    /* Pv     : vapor pressure, psia                 */
    /* Pvs    : sat. vapor pressure, psia            */
    /******

```

```

double Patm,Pv,Ps,RH;

    Patm = P_ATM;
    Ps   = Pvs(T);
    Pv   = H*Patm/(0.62198+H);
    RH   = Pv/Ps;
    if(RH >1.) RH =0.99;

    return(RH);
}
double ERH(double mdb, double TF)
{
    /******
    /* This sub. calc. equilibrium RH in decimal unit */
    /* RH : Relative Humidity [decimal unit] */
    /* TF : Temp, deg F (dry bulb) */
    /* TC : Temp, deg C (dry bulb) */
    /* mdb : EMC dry basis [decimal unit] */
    /* Use only for red wheat */
    /******

    double TC,RH;
    TC = (TF-32.)/1.8;
    RH = 1.- exp(-2.3008e-5*(TC+55.815)*pow(mdb*100.,2.2857));
    return(RH);
}
double M(int i)
{
    double a,b,m;

    a = EMC(Hold[0],Tai);
    b = EMC(Hold[0],Tgi);
    m = a+(a-EMC(Hold[0],Tnew[i]))*(EMCi-a)/(a-b);

    return(m);
}

double dM(int i)
{
    double dM,k,TK,M,Me;

    TK = (Told[i]-32.)/1.8 + 273.;
    k = 2.4e8*exp(-6144.0/TK);
    M = Mold[i];
    Me = EMC(Hold[i-1],0.5*(Told[i-1]+Told[i]));
    if (M > Me) return (0.);
    dM= -k*(M-Me)*dt/60.;
    return(dM);
}
/*****      END Subroutine      *****/.

```

APPENDIX D

PHYSICAL PROPERTIES OF GRAIN, AIR, AND WATER

The physical properties that were used in the calculation model was from the actual experiment of Epperly, D. R., (1990) and the thermodynamics property table of air and water, ASHARE (1985).

TABLE XI

PROPERTIES OF GRAIN(HARD RED WINTER WHEAT)

Property, unit	Value
Bulk density, kg/m^3	793.3
Particle density, kg/m^3	1440
Specific heat, $\text{J/kg}^\circ\text{C}$	1758
Thermal conductivity, $\text{W/m}^\circ\text{C}$	0.1461

TABLE XII
PROPERTIES OF WATER (AT 20°C)

Property, unit	Value
Density, kg/m^3	999.3
Specific heat, $\text{J/kg}^\circ\text{C}$	1758
Thermal conductivity, $\text{W/m}^\circ\text{C}$	0.1461

TABLE XIII
PROPERTIES OF AIR (AT 20°C)

Property, unit	Value
Density, kg/m^3	1.29
Specific heat, $\text{J/kg}^\circ\text{C}$	1.007

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